Document Title:	Document Number: ORAUT-OTIB-0046
Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Plant in Oak Ridge, Tennessee: Part 3 – Beta Radiation	Revision: 00 Effective Date: 06/22/2007 Type of Document: OTIB Supersedes: None

Subject Expert(s): George D. Kerr, Edward L. Frome, Janice P. Watkins, and William G. Tankersley

Site Expert(s): N/A

Approval:	Signature on File William G. Tankersley, Document Owner	Approval Date:	06/06/2007
Concurrence:	Signature on File John M. Byrne, Task 3 Manager	Concurrence Date:	06/05/2007
Concurrence:	Signature on File Edward F. Maher, Task 5 Manager	Concurrence Date:	06/05/2007
Concurrence:	Signature on File Kate Kimpan, Project Director	Concurrence Date:	06/12/2007
Approval:	Brant A. Ulsh Signature on File for James W. Neton, Associate Director for Science	Approval Date:	06/22/2007

☒ New ☐ Total Rewrite ☐ Revision ☐ Page Change

FOR DOCUMENTS MARKED AS A TOTAL REWRITE, REVISION, OR PAGE CHANGE, REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/22/2007	00	New technical information bulletin that provides background information on the Y-12 external dosimetry program related to film badge monitoring of beta radiation. Incorporates formal internal and NIOSH review comments. Attributions and Annotations section added. Added references and made editorial changes. No further changes occurred as a result of formal internal and NIOSH review of the Attributions and Annotations section. There is no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by George D. Kerr.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
BOW	beta open window
cm	centimeter
CER	Center for Epidemiologic Research
COC	Cincinnati Operations Center
DOE	U.S. Department of Energy
DU	depleted uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EU	enriched uranium
ev	electron volt (a unit of energy)
gal	gallon
GOW	gamma open window
GCW	gamma cadmium window
GM	geometrical mean
GSD	geometrical standard deviation
ICRP38	Publication 38 of the International Commission on Radiological Protection
hr	hour
HEU	highly enriched uranium
HP	Health Physics
ID	identification
in.	inch
K-M	Kaplan-Meier
keV	kilo electron volts (1 thousand electron volts)
kg	kilogram
lb	pound
m	meter
MDL	minimum detectable limit
MeV	mega electron volts (1 million electron volts)
ML	maximum likelihood
MLE	maximum likelihood estimate
mg	milligram
mm	millimeter
mR	milliroentgen (a physical dose unit approximately equal to 1 mrad)
mrad	millirad (a physical dose unit equal to 1/1000 of a rad)
mrem	millirem (a biological dose units equal to 1/1000 of a rem)
mrep	millirep (a physical dose unit approximately equal to 1 mrad)

n	neutron
NIOSH	National Institute for Occupational Safety and Health
NU	natural uranium
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
PIC	pocket ionization chamber
PLE	product limit estimate
ppm	parts per million
q-q	quantile-quantile
qtr	calendar quarter (13 weeks)
rem	roentgen equivalent man (a biological dose unit)
RPG	radiation protection guideline
RU	recycled uranium
SRS	Savannah River Site
SSN	Social Security Number
TEDE	total effective dose equivalent
TIB	technical information bulletin
TLD	thermoluminescent dosimeter
UCCND	Union Carbide Corporation, Nuclear Division
U.S.C.	United State Code
wk	week
yr	year
Y-12	Y-12 Plant, now the Y-12 National Security Complex
Z	atomic number
β	beta particle
γ	gamma ray
μg	microgram
§	section or sections

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. TIBs will be revised in the event additional relevant information is obtained. TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [EEOICPA; 42 U.S.C. § 7384l(5) and (12)].

2.0 PURPOSE

The purpose of this series of reports is to present definitive documentation about the development of the Y-12 film badge program from its beginning half a century ago to 1979, the end of the film badge period (McLendon et al. 1980; West 1993a). Parts 1 and 2 of this series discuss the use of film badges to monitor external exposures to gamma and neutron radiation at the Y-12 Plant (ORAUT 2005a,b). This report, Part 3, provides background information on the Y-12 external dosimetry program related to film badge monitoring of beta radiation. The principal source of beta radiation at the Y-12 Plant has been depleted uranium (DU) metals (Henderson 1991; Ashley et al. 1995).

A summary of the maximum likelihood (ML) methods used to estimate parameters for randomly left-censored lognormal data is provided in this report (Frome and Watkins, 2004). These parameters can be used to determine quarterly lognormal prediction densities for beta-particle dose to Y-12 worker populations. Tables of geometric means (GMs) and geometric standard deviations (GSDs) defining the prediction densities are supplied for 1947 to 1979 and can be used for sampling individual worker doses (ORAUT 2004a).

Graphical methods were used to evaluate the lognormal assumption for the quarterly dose data. Modified boxplots and quantile-quantile (q-q) plots with accompanying summary statistics supplied detailed information on quarterly doses and supported lognormal distributions for quarters after 1956. Quarterly data before 1956 were not found to fit a lognormal or other statistical distribution, and details of the monitoring policies and recording practices for this period confirmed that these data might not be suitable for use in estimating missing quarterly doses.

As an alternative, parameters for quarterly lognormal prediction densities before 1956 were obtained from ML regression based on data from a subgroup of 182 workers who were monitored regularly before and after 1961 and who worked in departments with potential for exposure to beta radiation. Although all employees were to be monitored with film badges from 1961 to 1979, before 1961 only workers with greater exposure potential were monitored (Watkins et al. 1993). As a consequence, it is to be expected that estimated doses based on the regression analysis of the subgroup data are favorable to claimants.

All statistical analyses were carried out using the R system (RDCT 2004). The R system is an integrated suite of free software for data manipulation, calculation, and graphical display. It can be run on a variety of UNIX® platforms and similar systems (including Linux and FreeBSD), Windows®, and Mac OS®. A detailed documentation on all aspects of the R system is available on the R Web page (*http://www.r-project.org*).

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 11.0.

3.0 FILM BADGE DOSIMETRY AT THE Y-12 PLANT

The first film badge dosimeter used at Y-12 was the same U.S. Atomic Energy Commission (AEC) film badge used at the Oak Ridge National Laboratory (ORNL) in 1949 (West 1993a) and described by Thornton, Davis, and Gupton (1961). This film badge was an AEC Catalog Number PF-1B film badge manufactured by the A. M. Samples Machine Company in Knoxville, Tennessee (Patterson, West, and McLendon 1957; West 1993b). The radiation-sensitive film in the PF-1B badge was enclosed in a protective stainless-steel case with a clip for attachment to clothing or a lanyard. One portion of the film was covered by a cadmium filter with a thickness of 1 mm to determine the dose from hard X-rays and gamma rays with energies from 100 keV to 3 MeV. The remaining uncovered portion of the film (open window) was used to determine the dose from beta particles or soft X-rays with energies less than 100 keV (Handloser 1959; Morgan 1961).

The above film badge was used until 1961, when a newer film badge dosimeter was adopted for use at all AEC facilities operated by Union Carbide Corporation Nuclear Division (UCCND) (Thornton, Davis, and Gupton 1961; McLendon 1963; McRee, West, and McLendon 1965). This film badge served as a security badge and provided monitoring of both routine and accident-related radiation exposures. As in the earlier PF-1B film dosimeter, a cadmium filter with a thickness of approximately 1 mm or mass density of 1,000 mg/cm^2 was included to measure the penetrating whole-body dose from hard X-rays and gamma rays. In addition, the film badges had an open window to measure beta radiation and to distinguish film exposures due to beta particles and soft X-rays. Plastic and aluminum filters were also incorporated into the UCCND film badge. The areas behind the plastic and aluminum filters were read, but these results were not used routinely in the evaluation of a worker's exposure to beta particles, X-rays, and gamma radiation at the Y-12 Plant (Sherrill and Tucker 1973).

In order to interpret a worker's dose from beta and gamma radiation by means of film badge dosimetry, it was necessary that the film be calibrated (Sherrill and Tucker 1973). The calibrations were done by exposing separate sets of film badges to known doses from high-energy beta particles and gamma rays. The film dosimeters were calibrated for beta radiation by placing them face down on a slab of natural uranium (NU) and for gamma radiation by exposing them to gamma rays from either a radium or ^{60}Co source (Souleyrette 2003). The calibration films were then developed and read to determine the response of the unshielded film to beta radiation, denoted as beta open window (BOW); the response of the film to gamma radiation, denoted as gamma open window (GOW); and the response of the film to gamma radiation through the cadmium filter, denoted as gamma cadmium window (GCW) (Sherrill and Tucker 1973).

After a worker's badge film was developed and read, the worker's exposure to gamma radiation was determined from the GCW (Sherrill and Tucker 1973). The GCW was used because any beta radiation would have been absorbed in the cadmium metal shield. The unshielded open-window area in the film dosimeter darkened when exposed to either beta or gamma radiation; therefore, it was necessary to compensate for the gamma-ray effect on the GOW before using it to estimate the exposure to beta radiation (BOW). To do this, the gamma exposure as determined from the film behind the GCW was used to estimate the reading that such an amount of gamma exposure would have produced in the film behind the GOW. This GOW value was then subtracted from the worker's total beta plus gamma exposure to determine the beta exposure from behind the BOW (Sherrill and Tucker 1973). At certain uranium facilities, film badge dosimeters were sometimes calibrated when covered with plastic bags that were used to prevent contamination of the film badges during use in dusty areas of the facilities. Film badges were never covered with plastic bags during use or calibration at the Y-12 Plant (Rutherford 2005).

Table 3-1 summarizes the various beta dose rates to skin from NU slabs that were used in film badge calibrations at the Y-12 Plant. These dose rates represent dose rates to the basal layer of skin (see, for example, NBS 1954; ICRP 1984, 2002). The basal layer of the skin on most body surfaces is at a range of depths between 5 and 10 mg/cm^2 with a mean range of approximately 7 mg/cm^2. The currently accepted value for the beta dose rate from an NU slab after passing through a tissue-equivalent plastic filter of 7 mg/cm^2 is approximately 233 mrad/hr (see, for example, IAEA 1974; Coleman, Hudson, and Plato 1983; DOE 2004). The radiation dose at a tissue depth of 7 mg/cm^2 is now referred to as the *shallow radiation dose*, rather than *skin dose*. Beta particles with energies less than approximately 60 keV are not able to penetrate to the basal layer at a skin depth of 7 mg/cm^2 (Figure 3-1). The radiations that contribute most significantly to the shallow (or skin) dose are beta particles with energies from approximately 60 keV to 4 MeV and photons with energies less than approximately 15 keV (ORAUT 2005c).

Table 3-1. Skin dose rates for slabs of natural uranium used in film badge calibrations at the Y-12 Plant.

Reference	Surface dose rate
Murray (1948a)[a]	270 mR/hr
Struxness (1951a)[a]	240 mrep/hr
McLendon (1963)	240 mrad/hr
McRee, West, and McLendon (1965)	240 mrad/hr
Jones (1971)	240 mrad/hr

a. These references note that the dose rate from gamma rays at surface of the NU calibration source was approximately 5 mR/hr.

A radium source enclosed in 0.5 mm of platinum was used initially for the calibration gamma-ray source (Struxness 1951a) and a ^{60}Co source was used starting in the early 1960s (UCNC 1963a). The film badges were exposed in air (no phantom), and the gamma radiation dose to the film badge was determined by the use of a Victoreen R-chamber that was exposed at the same distance from the gamma-ray source as the film badges (Struxness 1951a; McRee et al. 1965). The film badge dosimeters used at the Y-12 Plant typically exhibited about the same sensitivity to gamma and beta radiations; i.e., a 1-rem dose of beta particles yielded about the same response in the film as a 1-rem dose of gamma rays (Thornton, Davis, and Gupton 1961; Auxier 1967). Thus, the minimum detectable limits (MDLs) of the film badge dosimeters were assumed to be approximately the same for beta particles and gamma rays (Table 3-2). In 1949, neutron-sensitive films were added to the film badges for neutron dosimetry purposes (Struxness 1949a; ORAUT 2005b). The MDL of the neutron-sensitive films is estimated to be about 50 mrem for all years of use at the Y-12 Plant (ORAUT 2005b). There were only a few locations at the Y-12 Plant where neutron exposures were routinely possible; in these cases, personnel monitoring was provided by the neutron-sensitive film dosimeters (Emlet 1956).

The quarterly shallow (or skin) dose can be calculated from the recorded film badge doses using the equation:

$$D(\text{skin}) = D(\beta) + D(\gamma) + D(n) \tag{3-1}$$

where D(β) is the recorded dose from beta particles, D(γ) is the recorded dose from gamma rays, and D(n) is the dose from neutrons. The various component doses provided by Y-12 to CER for use in

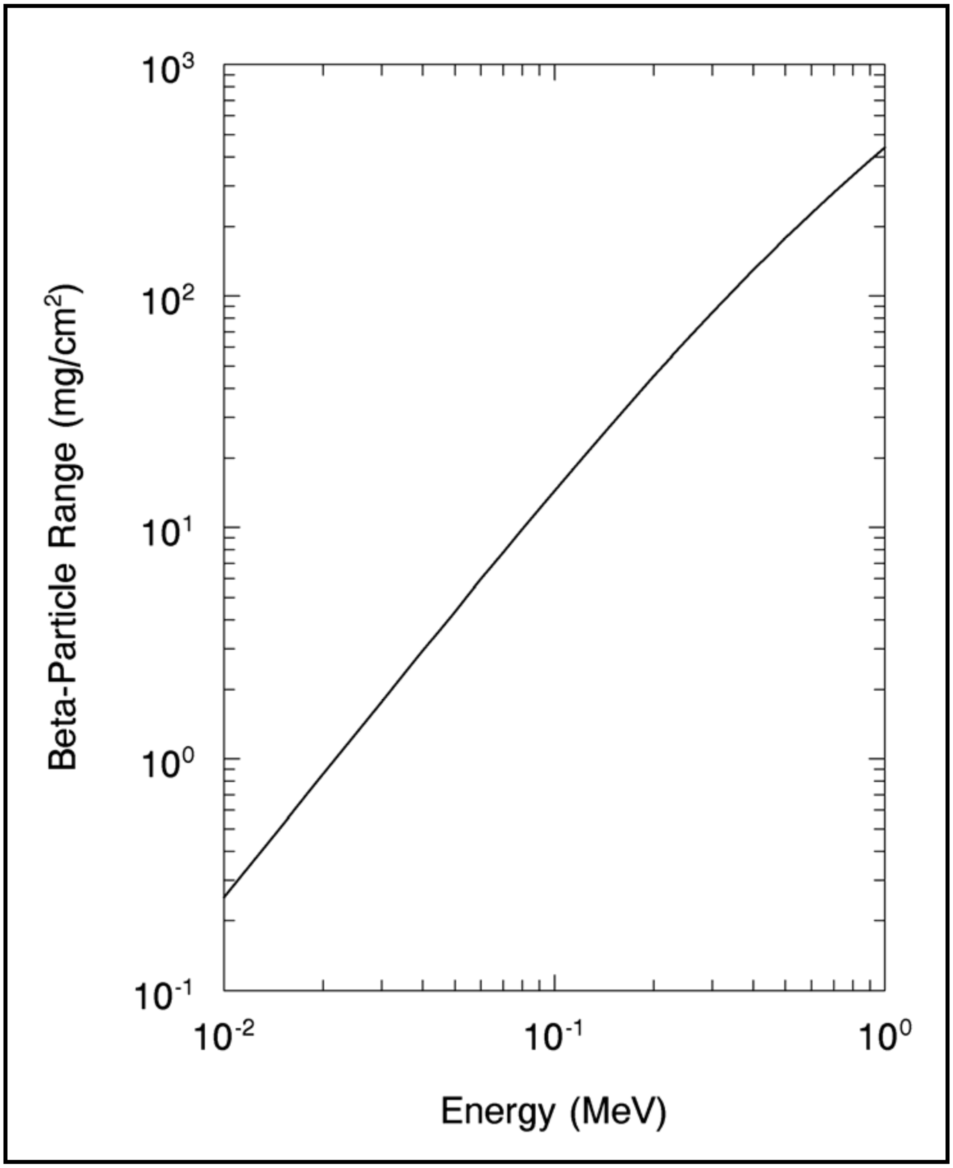

Figure 3-1. Range of beta particles in skin as calculated with the ESTAR computer program (Berger et al. 2005). These data can also be applied to other low Z materials used in photographic film packets and security credentials of film badge dosimeters.

previous epidemiology studies (Watkins et al. 1993) and to NIOSH in response to EEOICPA requests are either the recorded quarterly dose measurements after 1961 or those obtained by Y-12 as quarterly sums based on recorded monthly, biweekly, or weekly doses prior to 1961 (see Table 3-3). The quarterly deep (or penetrating whole-body) dose can be calculated using the equation:

$$D(\text{penetrating}) = D(\gamma) + D(n) \tag{3-2}$$

where D(γ) and D(n) are defined as in Equation 3-1. A comparison of Equations 3-1 and 3-2 shows that the quarterly recorded skin (or shallow) dose for a Y-12 worker should always be equal to or greater than that worker's quarterly recorded penetrating (or deep) dose.

Table 3-2. MDLs and assigned MDL doses (mrem) for film badge dosimeters used to measure beta and gamma radiation exposures at the Y-12 Plant.[a]

Period[b]	MDL	Assigned MDL
May 1948 to December 1949	30	30
January 1950 to December 1951	30	0
January 1952 to September 1952	50	50
October 1952 to December 1952	43	43
January 1953 to June 1954	50	50
July 1954 to December 1954	30	30
January 1955 to December 1957	30	15
January 1958 to October 1979	30	Not Applicable

a. ORAUT (2005d) and West (1993a)
b. Dates are approximate because the changes did not occur for all employees at the same time.

Table 3-3. Historical monitoring techniques and routine exchange frequencies for external radiation dosimeters at the Y-12 Plant.[a]

Period	Monitoring technique	Routine exchange frequency	Comments
1948–1949	Film badges, film pads, rubber finger rings, and PICs	Film pads, film rings and PICs daily, film badges weekly	Film pads and finger rings were used to measured beta doses to hands of uranium metal workers
1950–1958	Film badges, plastic finger rings	Weekly	Neutron-sensitive films were exchanged biweekly
1958–1960	Film badges	Monthly	
1961–1979	Film badges	Quarterly	Nearly all workers monitored
1980–1995	TLDs	Some quarterly, some annually, a very limited group on a monthly basis	Quarterly exchange if expected to receive more than 500 mrem; annual exchange if expected to receive less than 500 mrem
1996–present	TLDs	Mostly quarterly, some monthly	Workers monitored only if entering radiological areas.

a. ORAUT (2005d), Souleyrette (2003); West (1993a); McLendon (1962, 1958); Reavis (1958); Wollan (1954); Struxness (1951a).

Although early film badge dosimeters were relatively accurate for measuring beta dose, they were known to have over-responded significantly to low-energy photons (ORAUT 2005c, 2006a). The disparity between the responses of film behind the open window for low-energy photons and beta particles was well understood, as was the difference in response between low- and high-energy photons. The decision by the Y-12 Health Physics (HP) staff to evaluate the open-window readings using a calibration curve derived from NU simply took advantage of the conservatism associated with evaluating the soft X-ray response behind the open window using the NU calibration curve (ORAU 2005a, 2006a). In the rare case in which a worker was involved in an incident while engaged in radiological or nondestructive testing with an X-ray machine, the type of machine and its operating voltage were known; thus, the Y-12 HP staff was prepared to calibrate film using an appropriate energy spectrum of X-rays and to evaluate any unusual X-ray exposure incident (Patterson 1958).

3.1 1947 TO 1949

Management of the Y-12 Plant was assumed by UCCND in May 1947, and the mission changed from the electromagnetic enrichment of uranium to the processing and fabrication of uranium and other nuclear materials (ORAUT 2005a). The first experience related to the machining of uranium metal at the Y-12 Plant was in December 1947 in a shop in Building 9766 (Emlet 1952). In the spring of 1948, steps were taken for the transfer of certain weapons fabrication functions from Los Alamos to the Y-12 Plant, which were to be established in Building 9212 where the chemical processing of uranium had long been occurring. At that time, the responsibility for the study and monitoring of the uranium machining operations was transferred from a Special Hazards Group to a Health Physics (HP) Department established under the Medical Division at the Y-12 Plant (Emlet 1952).

The HP Department started an external dosimetry program in 1948 to monitor exposures to Y-12 workers in the Assay Laboratories, Radiographic Shop, Spectrographic Shop, and Machine Shops where uranium metals were handled (Murray 1948a,b; Struxness 1948a,b, 1949b). The radiation doses to the hands were measured using finger film pads (Larson 1949) or rubber finger rings containing film (Struxness 1949a) that were exchanged on a daily basis. The radiation doses to the whole body were measured using both Victoreen pocket ionization chambers (PICs) exchanged on a daily basis and PF-1B film badge dosimeters exchanged on a weekly basis (Souleyrette 2003; ORAUT 2006b). The MDLs for these dose measurements during the period from 1948 to 1949 were approximately 5 mrem for the PICs and approximately 30 mrem for the film in the finger pads, rubber finger rings, and badge dosimeters (Table 3-2).

The external monitoring data for 1948 to 1949 are not readily available by Social Security Number (SSN) and are not being supplied by Y-12 in response to EEOICPA requests (Souleyrette 2003). A report has been published of external monitoring data for the period from 1948 to 1949 that are available from previous epidemiological studies by the Center for Epidemiologic Research (CER) at Oak Ridge Associated Universities (ORAU) (ORAUT 2005d). The CER data have now been placed on the O Drive of the secure data server at the ORAU Cincinnati Operations Center (COC) for use in the dose reconstructions for workers at the Y-12 facility. The data on the O Drive have been linked to each worker's badge identification (ID) and SSN for dose reconstruction purposes (ORAUT 2005d).

3.2 1950 TO 1951

An extensive documentation of the worker radiological protection programs beginning in the 1950s is provided in the *Recycled Uranium Mass Balance Project for the Y-12 National Security Complex Site Report* (BWXT Y-12 2000). The external dosimetry program in place in 1950 was expanded to include all Y-12 personnel working with (1) depleted uranium (DU) metal, (2) discrete sources of gamma rays or beta particles, (3) X-rays, and (4) materials contaminated with fission products (McLendon 1960). The film pads and rubber film rings were both replaced with plastic film rings to assess the beta dose to the hands of DU metal workers (Struxness 1951b, 1952; Ballenger et al. 1953). The film badge and plastic film ring dosimeters were normally exchanged on a weekly basis (Table 3-3).

It was the policy at Y-12 in the 1950s to monitor all workers whose potential radiation exposure might exceed 10% of the radiation protection guidelines (RPGs) in effect at that time (Table 3-4). The RPG for the shallow or skin dose in 1950 and 1951 was 0.3 rem/wk (or 3.9 rem/qtr), and the 10% value for this RPG was 30 mrem/wk (or 390 mrem/qtr). Other workers at Y-12 were monitored because they had the potential to exceed the 10% value of the RPGs for the deep or penetrating whole-body dose from gamma and neutron radiation (ORAUT 2005a,b).

Table 3-4. Historical radiation protection guidelines (rem) for the Y-12 Plant.[a]

Period	Exposure period	Dose to lens of the eye	Dose to extremities[b]	Shallow or skin dose	Deep or penetrating whole-body dose	TEDE[c]
1944–1948	Day			0.1	0.1	
1949–1950	Week			0.3	0.3	
1951–1954	Week		1.5	0.3	0.3	
1955–1957	Week	0.3		0.6[d]	0.3	
1958	Week	0.3	1.5	0.6[e]	0.3[f]	
1959–1960	Quarter Year	1.2	25 75	6[e]	3[f]	
1961–03/29/1977	Quarter Year	 5	25 75	10 30	3[f]	
03/30/1977–1988	Quarter Year	 15	25 75	5 15	3 5	
1988–11/30/1992	Year	15	50	50		5
12/01/1992–Pres.	Year	15	50	50		5[g]

a. Wiley (2004).
b. The extremities are defined typically as the hands and arms below the elbow and the feet and legs below the knee.
c. DOE has used the total effective dose equivalent (TEDE) to limit the sum of the internal and external whole-body (effective) doses since 1989.
d. The actual date of change from 0.3 rem/wk to 0.6 rem/wk for the skin dose was the 10th week of 1955 or March 1955 (West 1955, 1956).
e. Accumulated dose not to exceed 10(N-18) rem, where N is the age in years.
f. Accumulated dose not to exceed 5(N-18) rem, where N is the age in years.
g. Accumulated dose not to exceed N rem, where N is the age in years.

Dosimetry practice was to record weekly open-window dose to the basal layer of the skin from beta particles or the penetrating doses from gamma rays behind the cadmium filter as zero if they were less than 30 mrem (Table 3-2). There are inconsistencies in the recorded dose records that appear to be due to changes in the way doses were originally recorded before being computerized or to typing mistakes in the transfer of the recorded doses to a computer system using keypunch cards. For example, there was only one positive gamma dose of 65 mrem among the 268 quarterly doses for the 148 workers monitored in 1950, no positive quarterly beta doses for the 148 workers monitored in 1950 or the 184 workers monitored in 1951, and no positive gamma doses among the 406 quarterly doses for the 184 workers monitored in 1951. The recorded gamma dose of 65 mrem could be a punch card mistake because there is no recorded penetrating dose for this worker. There are, however, 58 quarterly skin doses recorded for 45 workers in 1950 and 56 quarterly skin doses recorded for 48 workers in 1951 that range from a low of 36 mrem to a high of 1,800 mrem. Thus, it appears that the original intent was to computerize only the skin and penetrating doses and not the beta or gamma doses for the period from 1950 to 1951 [1].

3.3 1952 TO MID-1956

The documented dosimetry policy at the Y-12 Plant during this period was to assign the MDL dose for weeks with results less than the MDL for either beta or gamma radiation (Table 3-3). The MDL was estimated to be 50 mrem during weeks 1 to 38 of 1952, 43 mrem during weeks 39 to 52 of 1952, and 50 mrem during all of 1953 and weeks 1 to 30 of 1954 (ORAUT 2006a,b; West 1993). For the remainder of 1954, all of 1955, and the first half of 1956, the MDL was 30 mrem (ORAUT 2006a,b; West 1993). The assigned MDL dose was recorded as due to either beta or gamma radiation according to a worker's potential type of exposure as judged by the HP staff (West 1981); that is, the MDL was assigned to gamma rays and to penetrating radiation for persons having potential for that kind of exposure. For persons working with NU or DU, which has mainly a shallow (or beta particle) exposure potential, the MDL was assigned to skin dose. In practice, however, weekly doses less than the MDL were often left blank in the computer records for the Y-12 film badge program.

In 1981, a discrepancy was noted in the penetrating radiation doses recorded for Y-12 workers in 1954 (Beck 1981; West 1981). The average yearly value for a Y-12 worker in 1954 was only about 10 mrem, whereas it was several hundred mrem for 1952, 1953, and 1955. A review of the 1952–1955 data by the Y-12 Plant staff indicated that many workers assigned to departments having a penetrating dose potential showed elevated shallow (or skin) doses in 1954 (West 1981). However, these same workers showed elevated penetrating radiation dose and low shallow (or skin) dose in 1953 and 1955. For a total of 61 workers, it was decided to exchange the penetrating and shallow (or skin) doses in the computer records for the Y-12 film badge program in 1954. A list of personnel (and SSNs) for whom 1954 penetrating and skin dose records were reversed is given in Attachment 2 of West (1981). The 1981 memorandum by West and the 1981 memorandum by Beck are available on the secure data server at the ORAU-COC.

For the period from 1952 to mid-1956, the differences between the various doses summed to obtain the skin and penetrating doses (see Equations 3-1 and 3-2) now appear to be random, with some being greater and others being smaller than the skin or penetrating doses. In general, comparisons between the skin and penetrating doses and the sums of the beta, gamma, and neutron doses used to obtain these doses are highly consistent during the film badge program at the Y-12 Plant for 1952 to 1979.

3.4 MID-1956 TO 1961

The radiation dosimetry policy to monitor only selected workers (approximately 10-20%) of the workforce was continued (Watkins et al. 1993; ORAUT 2005a). Line supervision at the Y-12 Plant, with the assistance of the HP Department, decided which groups and which persons in a group would be assigned to the film badge monitoring program and kept the list of assigned workers up to date (Patterson, West, and McLendon 1957; West 1993b). The workers typically selected for the program were those whose potential radiation exposure might exceed 10% of the RPGs in effect at that time. For example, the 10% value of the RPG for the skin dose was 60 mrem/wk (or 780 mrem/qtr) from 1956 through 1958 and 600 mrem/qtr from 1959 through 1960 (Table 3-4). The line supervisor initiated requests for the HP Department to either add or remove workers from the film badge program. The HP staff then forwarded the request to the monitoring laboratory, with all necessary data on a formal request card, and the monitoring laboratory prepared two badges for workers added to the external monitoring program, one with a black face and one with a white face, to be worn during alternate badge exchange periods (Table 3-3). Monthly doses for a film badge dosimeter that read less than the MDL were recorded as 15 mrem, half of the MDL (Table 3-2), and entered as beta radiation doses.

In April 1958, the external monitoring of 704 workers was reviewed during the switch from a weekly to a monthly badge exchange frequency (McLendon 1958; Reavis 1958). Some of the factors considered in the review were (1) type of exposure expected, (2) exposure potential involved, (3) typical experience over the last year in relation to average and high exposures, (4) expected changes in this typical experience in the near future, and (5) statistical limit of errors and detectability. As a result, it was decided to make a number of changes in the external monitoring program. The reasons for and the nature of the changes were discussed with, and agreed on, by supervision in all the departments (McLendon 1958). Of the 704 workers involved in the review, 89 were dropped from the external monitoring program and 615 were selected to remain in the program. The workers remaining in the monitoring program were distributed among departments as follows (department number in parenthesis): 207 in the A Wing, H2 & F Area (2703), 58 in Z Area (2701), 53 in Product

Control (2665), 45 in Production and Inspection (2233), 38 in H-1 Foundry (2702), 34 in Product Processing (2617), 31 in the 9215 Rolling Area (2793), 25 in the Fire Department (2093), 24 in Uranium Chip Recovery (2618), 23 in Mechanical Inspection (2044), and 77 in 10 other departments such as Electrical Maintenance (2004), Medical Department (2090), Guard Department (2091), Health Physics (2108), Plant Superintendent and Directors (2200), Shift Superintendents (2205), Special Testing (2231), Development Operations (2301), Product Chemical (2616), and Chemical (2619). The review appears to have included only workers who were being monitored for exposures to beta and gamma radiation and did not include workers who were being monitored for exposures to neutron radiation on a biweekly film badge exchange frequency (ORAUT 2005b).

On June 16, 1958, an unexpected nuclear excursion occurred in the C Wing of Building 9212 at the Y-12 Plant (UCNC 1958). An enriched uranium (EU) nitrate solution, sufficient to become critical, was drained from a bank of “always safe geometry” cylinders with small diameters into a 55-gal drum during an operation in which only water was expected to be in the cylinders. Eight workers, who were not expected to be exposed to radiation during this operation and were not wearing film badge dosimeters, received penetrating doses from gamma rays and neutrons ranging from about 23 to 365 rem (Hurst, Ritchie, and Emerson 1959). These eight workers were identified by neutron activation of an indium strip in their ID badges and of sodium in their blood. Their radiation doses were estimated using each worker’s blood sodium activation data and other data obtained from a controlled physical mockup of the accident (Callihan and Thomas 1959). More information on these eight workers and 23 other workers who were in the area of the nuclear excursion but exposed to much smaller radiation doses based on neutron activation of the indium foil in their ID badges is available on the O Drive of the secure data server at the ORAU-COC (ORAUT 2006c).

3.5 1961 TO 1979

As a result of the 1958 criticality accident at the Y-12 Plant, a program was instituted in 1961 to monitor all Y-12 workers for external radiation exposure with the use of a newer dosimeter system that was an integral part of the worker’s ID badge and contained components for both routine and accident-related dosimetry (Thornton, Davis, and Gupton 1961; McLendon 1963; McRee, West, and McLendon 1965; ORAUT 2006b). The film badges were read quarterly (Table 3-3) and the readings were recorded as determined, even when the readings were less than the MDL and so essentially not different from zero. The external doses to Y-12 workers were always determined from the film readings behind the cadmium filters and open windows of the film badges (Sherrill and Tucker 1973). The film areas behind the plastic and aluminum filters in the newer film badge dosimeters were read and recorded, but they were not used in the normal evaluation of worker doses. The film badge period ended in 1979 as film badge dosimeters at the Y-12 Plant were largely replaced by thermoluminescent dosimeters (TLDs) (McLendon et al. 1980; Howell and Batte 1982; Oxley 2001).

4.0 MAJOR SOURCES FOR EXPOSURES TO BETA PARTICLES AT THE Y-12 PLANT

A chronology of metal processing and fabrication at the Y-12 Plant during the film badge dosimetry program is provided in Table 4-1 (Wilcox 2001). The main function of the Y-12 Plant in the late 1940s and 1950s was the processing and fabrication of uranium components for nuclear weapons. Since then, the Y-12 Plant has become the center for handling, processing, manufacture, and storage of uranium materials and nuclear weapons components (BWXT Y-12 2000).

Material processing at the Y-12 Plant has included the recovery of both EU and recycled uranium (RU) from the Y-12 site and other sites operated by DOE (BWXT Y-12 2000). Material processing

Table 4-1. Chronology of metal processing and fabrication at the Y-12 Plant during the film badge dosimetry program, 1947 to 1979.[a]

Year	Event
1947	Y-12 undertakes task of reducing K-25 EU to metal and fabrication.
1948	Machining of NU and EU on a small scale is initiated early in the year.
1949	The first HEU weapon parts are manufactured at Y-12 and shipped to Los Alamos National Laboratory.
	The first DU machining is started in Building 9766.
1953	Expanded facilities for uranium casting and machining are put into production in the E Wing of Building 9212.
1957	Installation is completed of a primary rolling mill in Building 9215 and larger pressing facilities for fabricating uranium are installed in Building 9204-4.
	Production of HEU weapon parts starts in Building 9998.
1958	Installation is completed of a heavy shop for uranium fabrication in 9204-4. The shop included a press with a rated capacity of 7,500 tons.
	A 66-in.-wide rolling mill for work on DU parts and an a 42-in.-wide rolling mill for work on EU parts are installed in Building 9215
1959	Fabrication of parts from thorium is started at Y-12.
1963	Facilities and expertise are developed to process uranium, thorium, and other materials in enclosed and/or closely controlled atmospheres. Production operations include rolling, forging, machining, and dimensional inspection.
1968	Efforts are begun to procure much larger and more accurate turning machines for producing weapon parts. The turning machines were installed in Building 9201-5 in 1971 and 1972.

a. See Wilcox (2001).

and fabrication at Y-12 has included NU, DU, thorium, and ^{233}U. The areas at Y-12 involved in processing these different materials are discussed in more detail in the following sections.

4.1 NATURAL URANIUM

When uranium is separated from its ore, the resulting mixture is referred to as natural uranium. NU consists of about 0.72% by weight of ^{235}U with the remainder being almost entirely ^{238}U. In March 1948, the first NU was machined at Y-12 for use in the shielding of gamma rays from radium sources (Wilcox 2001). In general, the same buildings and facilities were used for the processing and fabrication of both NU and DU metals. The majority of the DU operations at the Y-12 Plant were housed in Buildings 9201-5, 9204-4, 9206, 9215, 9766, and 9998 (Henderson 1991; Ashley et al. 1995; BWXT Y-12 2000; Wilcox 2001; ORAUT 2005e).

4.2 DEPLETED URANIUM

Uranium with some of its ^{235}U extracted is known as depleted uranium. DU metal is responsible for the majority of the shallow doses to workers at the Y-12 facility (Henderson 1991; Ashley et al. 1995). Historically, the workers who have received the highest doses from beta radiation have been those in the H-1 Foundry (Building 9998), the Arc-Melt Facility and Machine Shops in Building 9201-5, the Forming Area in Building 9204-4, and the Product Certification Groups (Ultrasonic Testing, Mechanical Properties, Dimensional Inspection, and Radiography).

Gamma radiation from uranium is normally not the controlling challenge to radiation protection in uranium facilities (DOE 2004). For example, the contact gamma radiation field is less than 10 mrem/hr, while the contact beta radiation field from NU or DU is approximately 240 mrem/hr (Table 3-4). The dominant radiation hazard in facilities requiring contact work with unshielded forms of uranium metal is the beta radiation field. Figure 4-1 shows the estimated beta dose rates from a

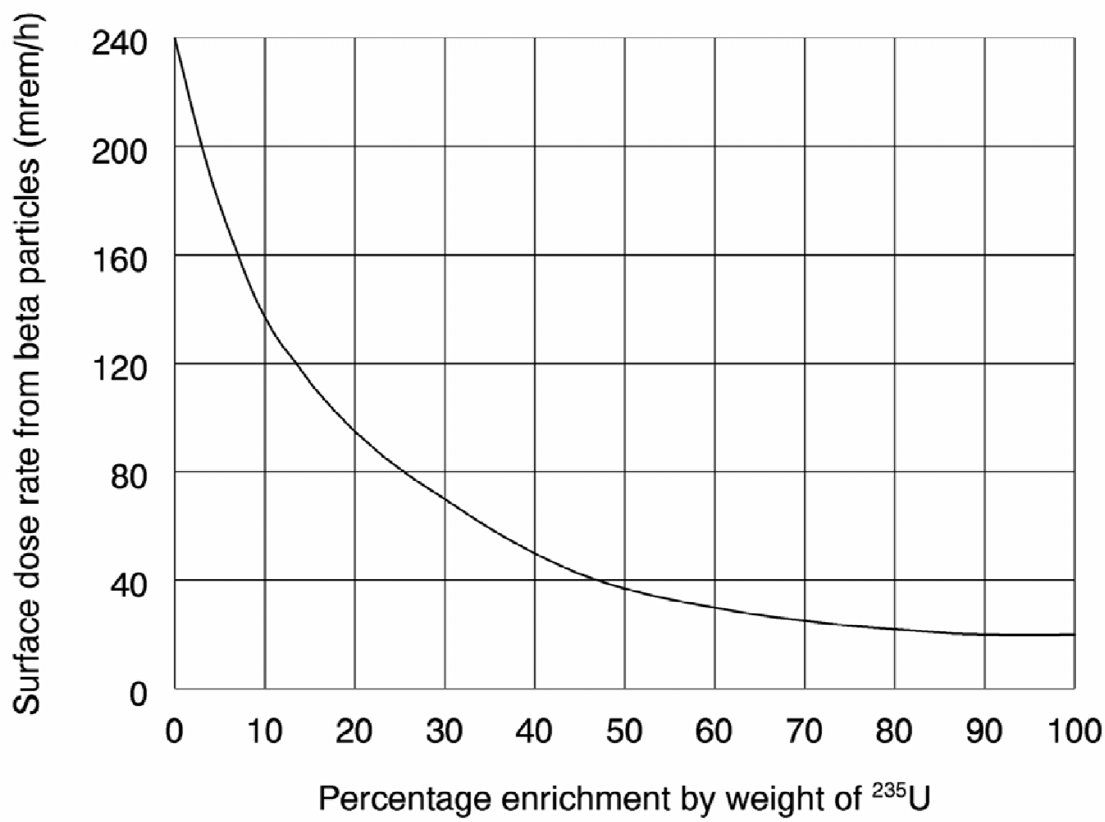

Figure 4-1. Estimated dose rates from beta particles at the surface of a semi-infinite slab of uranium metal for various enrichments of ^{235}U (DOE 2004).

semi-infinite slab of uranium metal of various enrichments (DOE 2004). For uranium enrichments up to about 30%, the beta radiation field is dominated by contributions from ^{238}U decay products, and the beta radiation comes from the decay product ^{234m}Pa and to a lesser extent from ^{234}Th (Table 4-2). Thus, for uranium of these enrichments, one is dealing essentially with the 2.29-MeV (E_{max}) beta particles from ^{234m}Pa, the most energetic contributor to the beta exposure (DOE 2004). The beta-particle dose contribution for uranium enrichments above 30% is considerably less due to the much lower energies of the beta particles emitted by the ^{231}Th decay product of ^{235}U (Table 4-2).

Processes that separate and sometimes concentrate uranium decay products such as ^{234m}Pa and ^{234}Th are not uncommon in DOE uranium facilities (Struxness 1954a,b; Henderson 1991; DOE 2004). Surface dose rates from beta particles on the order of 1 rem/hr to 20 rem/hr have been observed in such circumstances. Exposure control is complicated because considerable contact work takes place in some DOE facilities that process uranium metal for weapons components.

Beta doses to the skin, extremities, and sometimes the lens of the eye can be limiting in facilities that process unshielded low-enrichment NU or DU. However, the actual beta doses to these body tissues depend on the energies of the beta particles and the thickness and types of intervening shielding of these body tissues. Shielding against beta particles is provided by such common items as clothing, aprons, gloves, eyeglasses, and face shields (Struxness 1954a,b; Henderson 1991; DOE 2004; ORAUT 2005c).

Table 4-2. Maximum energies and intensities of the beta particles from common radiation sources at the Y-12 Plant.[a]

Radionuclide	Decay product	Maximum beta energy (MeV)	Beta intensity (%)
Uranium metal			
U-238	Th-234	0.095 0.096 0.199	6.2 18.6 72.5
	Pa-234m	2.28	98.6
U-235	Th-231	0.205 0.287 0.305	15 49 35
Thorium metal			
Th-232	Ra-228	0.0389	100
	Ac-228	0.983 1.014 1.17 1.74 2.08	7 6.6 32 12 8
Th-228	Pb-212	0.158 0.334 0.573	5.2 85.1 9.9
	Bi-212	1.59 2.246	8 48.4
	Tl-208	1.28 1.52 1.80	25 21 50
Uranium-233			
U-232	Pb-212	0.158 0.334 0.573	5.2 85.1 9.9
	Bi-212	1.59 2.246	8 48.4
	Tl-208	1.28 1.52 1.80	25 21 50
Recycled uranium impurities			
Pu-241		0.021	100
Tc-99		0.294	100

a. Maximum beta-particle energies and intensities taken from Shleien, Slaback, and Birky (1998).

4.3 ENRICHED URANIUM

EU is uranium that has been processed so that it contains more than 0.72% by weight of ^{235}U, and highly enriched uranium (HEU) contains more than 20% by weight of ^{235}U. The main facilities involved in the fabrication and processing of EU have been Buildings 9212 and 9206 (BWXT Y-12 2000). Until the early 1970s, chemical processing of EU occurred in the Building 9212 Complex. Afterward, chemical processing, following virtually the same procedure and using nearly identical equipment, occurred in Building 9206. Relatively small amounts of HEU metal were handled at any time because of its critical mass of only 48 kg (22 lb) (Table 4-3).

The original mission of Building 9212 during World War II was to recover HEU from the electromagnetic separation process project at Y-12 (BWXT Y-12 2000). Following World War II, Building 9212 was expanded to accommodate the increased production of EU from the Oak Ridge

Table 4-3. Properties of nuclear explosive nuclides (NRC 2005).

Nuclide	Critical mass (kg)	Main gamma energies (MeV)
U-233	16	2.6 from Tl-208
U-235	48	0.19
Pu-239	10	0.41

Gaseous Diffusion Plant (K-25) and to provide capability for the recovery of EU from waste materials. In 1948, structures were erected in the spaces between the existing A, B, C, and D Wings and designated A-1, B-1, C-1, and D-1 Wings. Another structure was added in 1951 adjacent to the D-1 Wing and designated the E Wing. The purpose of the E Wing was to facilitate the casting and machining of uranium components. A uranium hexafluoride conversion facility in the D Wing was shut down in 1964, which essentially halted the introduction of new HEU metal into the weapons stockpile. Since 1964, all HEU weapons components have been produced with uranium recovered from retired weapons and from production scrap. Three functions of the Building 9212 Facility that have contributed significantly to the shallow dose from beta particles are (1) casting of HEU metal (for weapons, storage, or other uses); (2) accountability of HEU from Plant activities (quality evaluation, casing, and storage); and (3) recovery of HEU to a form suitable for storage (from Y-12 Plant and commercial scrap).

Building 9206 has several related structures that house support services, process services, and equipment, all of which are considered inclusively as the 9206 Facility (BWXT Y-12 2000). These other structures are 9768, 9720-17, 9409-17, 9510-2, 9767-2, and the east and west tank farms. EU processes, activities, and missions of the 9206 Facility have included (1) recovery of EU and RU from Y-12 programs and other sites (1947 to 1994); (2) production of uranium compounds for other sites (1949 to 1972); (3) conversion of UF_6 to UF_4 to uranium metal for weapons (1954 to 1964); (4) casting and machining of HEU for weapons (1955 to 1965); (5) recovery of HEU from Savannah River Site (SRS) solutions and other scrap for return to SRS as uranium metal (1972 to 1989); (6) conversion of excess HEU metal for the Portsmouth Gaseous Diffusion Plant (1980 to 1985); and (7) storage of in-process materials (1950 to present). Non-EU processes, activities, and missions of the 9206 Facility have included (1) recycling DU chips (1951 to late 1950s), (2) production of uranium compounds for other sites (1949 to 1972), (3) canning of normal-assay uranium slugs for nuclear reactor use (1950 to 1952), and (4) storage of in-process materials (1950 to present).

From about 1949 to 1964, the Y-12 Plant received cylinders of 93.5%-enriched UF_6 as feed material for nuclear weapon parts production (ORAUT 2005e). After 1964, the majority of the HEU processed at the Y-12 Plant was recycled from weapons stockpiles. Uranium recycling and purification processes at Y-12 continue to the present. RU is uranium that has been irradiated in a reactor so that it contains transuranic material (^{239}Pu and ^{237}Np), fission products (^{99}Tc), and reactor-generated uranium products (^{236}U) (BWXT Y-12 2000). Thus, the processing and reenrichment of RU might represent an increased potential radiation hazard for occupational exposure that is greater than that normally associated with the processing of unirradiated uranium. Y-12 has proactively evaluated the RU materials against a specification that would maintain uranium as the dominating dose hazard for both external and internal radiation exposures (ORAUT 2005e). An alpha-particle ratio was used to ensure that the relative internal hazard of an emitter of alpha particles other than uranium was not significantly greater than the relative internal hazard of uranium, and both a beta-particle ratio and a total fission product specification were used to ensure that there would be no significant addition to the external radiation exposure of Y-12 workers (BWXT Y-12 2000).

4.4 THORIUM

The processing and fabrication of thorium metals at Y-12 began in the late 1950s and early 1960s (West 1965; Wilcox 2001; ORAUT 2005e). Thorium metal in pellet form was pressed into electrodes and two arc-melts were made. The metal from these melts was then pressed or rolled, formed, and machined. Metal scraps and chips were salvaged and pressed into electrodes to be used in the arc-melting process. The buildings housing these activities were as follows: (1) pellet and scrap preparation, arc-melting, crop and trim sawing occurred in Building 9201-5, (2) mold press sintering, ingot forging and annealing after the first cold roll, and final inspection and assembly were performed in Building 9204-4, (3) ingots were canned before the first cold roll in Building 9201-1, (4) cold and hot rolling were conducted in Building 9215, (5) decanning, cleaning, and final plating were done in Building 9206, (6) machining activities were conducted in Building 9766, and (7) development activities were carried out in Building 9202 (ORAUT 2005e; McRee, West, and McLendon 1965; McLendon 1963). In general, the same buildings and facilities were involved in the processing and fabrication of both thorium and DU metals.

4.5 URANIUM-233

Irradiation of thorium in a reactor is the source for ^{233}U, which has fission properties similar to ^{239}Pu (Table 4-2). For several years in the 1960s and 1970s, the Y-12 Plant was involved in the processing and fabrication of metal parts from ^{233}U (West and Roberts 1962; West 1974). This was accomplished by chemical conversion of a nitrate solution of ^{233}U to a metallic form and metallurgical fabrication to obtain the desired parts (West and Roberts 1962). The processing and fabrication of ^{233}U presented two major radiation protection problems: (1) it was a major internal radiation hazard because its high specific alpha-particle activity was about 150 times greater than other uranium routinely processed at Y-12 (West and Roberts 1962), and (2) it was a major external radiation hazard because the ^{232}U decay product of ^{233}U has a very high beta-particle emission rate, as noted in Table 4-2, and a very high gamma-ray emission rate, as noted in Table 4-3.

Because of the potential radiation hazards of working with ^{233}U, all operations were doubly contained (West and Roberts 1962; West 1974). The operations were carried out in the controlled atmosphere of Building 9205 using hoods that had been converted to gloveboxes by the installation of plastic hood fronts equipped with glove ports. The inlet and outlet ventilation was filtered and the ambient pressure in the box was maintained at a negative pressure of 0.2 in. of water in relation to that in the room. Calculations indicated that special gamma-ray shielding was not required because the operations were short-term and involved limited amounts of material (West and Roberts 1962; West 1974). However, extensive area and personnel monitoring for external radiation was provided by HP during the operations. The use of gloveboxes and remote handling resulted in minimal beta doses to the skin or hands of the Y-12 workers who were involved in the processing and fabrication of metal parts from ^{233}U (West and Roberts 1962; West 1974).

5.0 <u>FILM BADGE RESPONSE TO DIFFERENT SOURCES OF BETA PARTICLES</u>

The film badge used at Y-12 from 1948 through 1960 (Section 3.0) had a completely open window over the film packet, and the film packet used to protect the film against light and humidity had a thickness of approximately 25 to 30 mg/cm^2 over the front surface of the film (Dudney 1956; ICRU 1997). This thickness stopped essentially all beta particles with maximum energies less than approximately 150 keV from penetrating the film packet (Figure 3-1) and from producing a film response. The film badge used at Y-12 from 1961 through 1979 (Section 3.1) had an open window covered by security credentials with a thickness of approximately 50 mg/cm^2, so the total thickness over the front surface of the film was approximately 80 mg/cm^2 (Thornton, Davis, and Gupton 1961).

This thickness stopped essentially all beta particles with maximum energies of less than approximately 300 keV from penetrating the open window over the film (Figure 3-1) and from producing a film response. These somewhat different responses to low-energy beta particles were taken into account in the calibration factors obtained with an NU source.

Beta particles are emitted with a spectrum of energies, and the average beta-particle energy is about one-third of the maximum beta-particle energy (E_{max}). Figure 5-1 shows the energy spectra of the beta particles from NU as calculated using the DEXRAX code from the ICRP38 computer program package (Eckerman et al. 1994; Eckerman 2003). The maximum energies of each of the beta-particle spectra shown in Figure 5-1 are the same as those listed in Table 4-2, but the energy spectra are the composite energy spectra of all the beta particles emitted by the ^{231}Th decay products of ^{235}U and ^{234}Th and the ^{234m}Pa decay products of ^{238}U. Most of the shallow dose to the skin and nearly all the response in the film emulsion behind the open window of the film badge comes from the ^{234m}Pa decay product of ^{238}U (E_{max} = 2.28 MeV). The beta particles from the ^{231}Th decay product of ^{235}U (Emax = 199 keV) and the ^{234}Th decay product of ^{238}U (Emax = 305 keV) are highly attenuated by the paper jacket of the film packet in the badge used from 1948 to 1961 and by both the paper jacket of the film packet and the security credentials over the open window of the film badge used from 1961 to 1979 (Section 3.0).

Figure 5-2 shows the composite energy spectra of the beta particles from decay products of so-called 1-yr thorium. The decay products of ^{232}Th and ^{228}Th are in radioactive equilibrium in thorium ore, but the chemical separation of these isotopes to produce thorium metal affects the radioactive equilibrium of the thorium decay products for periods of more than 20 years (Schneider et al. 1999). The radioactivity of the thorium in the metal decreases rapidly at times less than one year, approaches a minimum at approximately five years, and increases as radioactive equilibrium of the decay products is established at approximately 50 years after chemical separation of the thorium metal from the thorium ore. Most of the thorium metal at Y-12 was processed within one year following chemical separation from the thorium ore (West 1965). Figure 5-3 shows the composite energy spectra from decay products of ^{232}U, which occurs as contaminates in reactor-produced ^{233}U. Uranium-233, like ^{239}Pu, is a long-lived fissile isotope produced in reactors by neutron capture in an abundant naturally occurring isotope (i.e., ^{239}Pu by neutron capture in ^{238}U and ^{233}U by neutron capture in ^{232}Th) (Kang and von Hippel 2001). The amount of ^{232}U contaminant in the ^{233}U processed at Y-12 was measured to be 47 ppm or 47 µg of ^{232}U/g of ^{233}U (Chew 2005), and the emission of beta particles per gram of ^{233}U would be 47 times that shown in Figure 5-3. The energy spectra of the beta particles from 1-yr thorium (Figure 5-2) and ^{232}U (Figure 5-3) indicate that the skin dose would be adequately measured by film badges because the number of high-energy beta particles from these metals is comparable to the number of high-energy beta particles from an NU calibration source.

In practical monitoring of beta particles, the exposure geometry is usually unknown and quite variable, but the source of the beta particles is usually known (the beta-emitting isotope, fission products, uranium metal, thorium metal, etc.). After the filtration of the lowest energy components by the paper jacket and security credentials over the front of the film, the energy spectrum of the beta particles varies only slowly with the source-to-film distance (i.e., with the thickness of the intervening air). In addition, a 1-MeV beta particle can travel over 4 m in air (Berger et al. 2005). Therefore, a fairly good calibration can be achieved with a standard source of the same beta emitter as the one whose beta radiation is to be monitored, especially if the radiation is diffusely incident on the body (Ehrlich 1962). Thus, the beta dose readings at a uranium facility were expected to be reliable for film badge dosimeters calibrated with an NU slab (the standard technique until the 1980s), and the uncertainties in the beta dose readings were approximately equal to those for gamma dose readings (Morgan 1961). The MDL of the dose measurements for gamma rays and beta particles was estimated to be approximately 30 mrem for most of the film badge period at the Y-12 Plant (Table 3-2). Thus, there

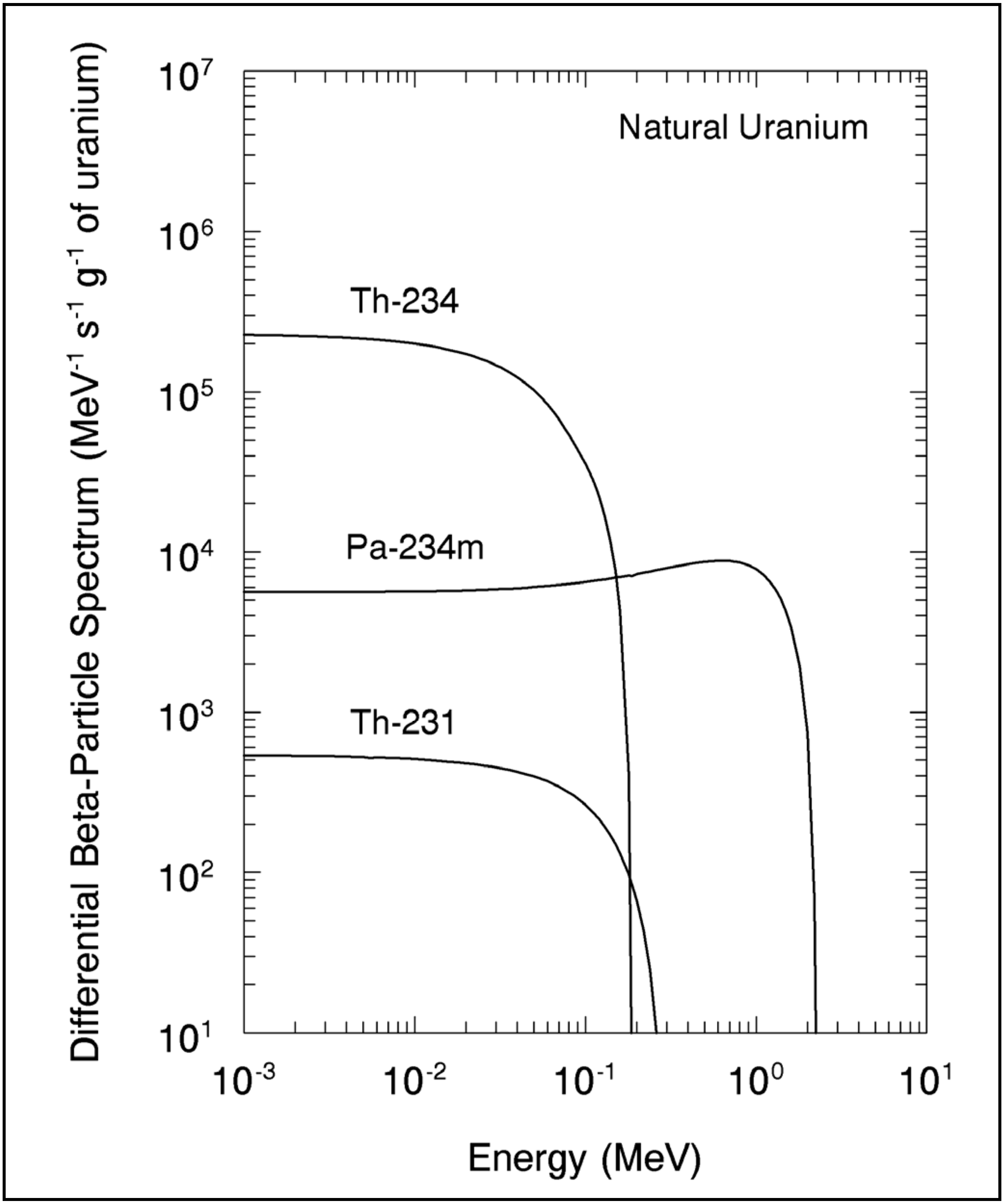

Figure 5-1. Energy spectra of beta particles from the decay products of NU as calculated using the DEXRAX code from the ICRP38 computer program package (Eckerman 2003). NU is assumed to be 0.72% by weight ^{235}U, the remainder being almost entirely ^{238}U.

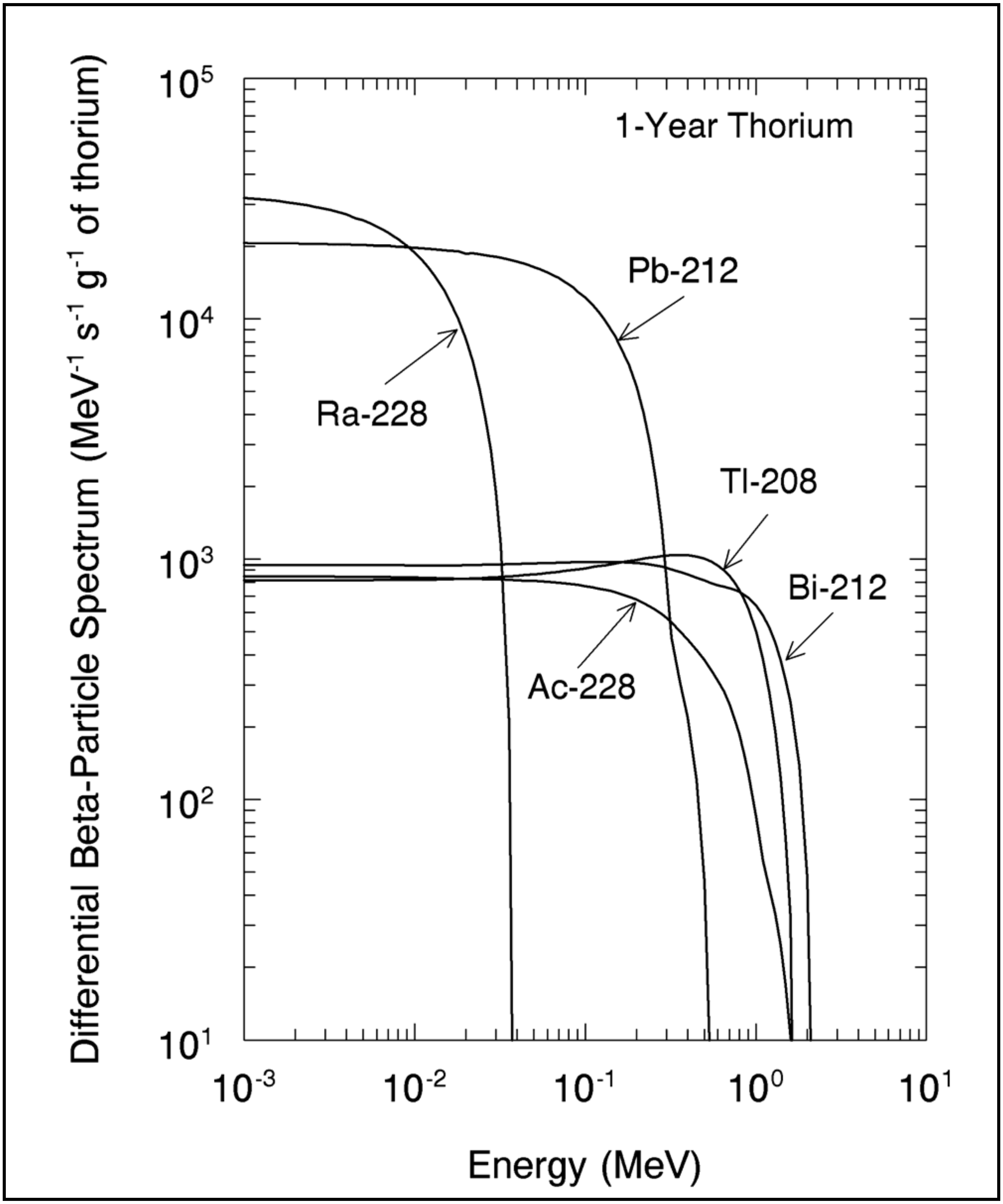

Figure 5-2. Energy spectra of beta particles from the decay products of 1-yr thorium as calculated using the DEXRAX code from the ICRP38 computer program package (Eckerman 2003). The activity of the decay products of 1-yr thorium is taken from Schneider et al. (1994, Table 3.1.5). All beta particles from ^{228}Ra are attenuated by the paper jacket on the film packet in the badge.

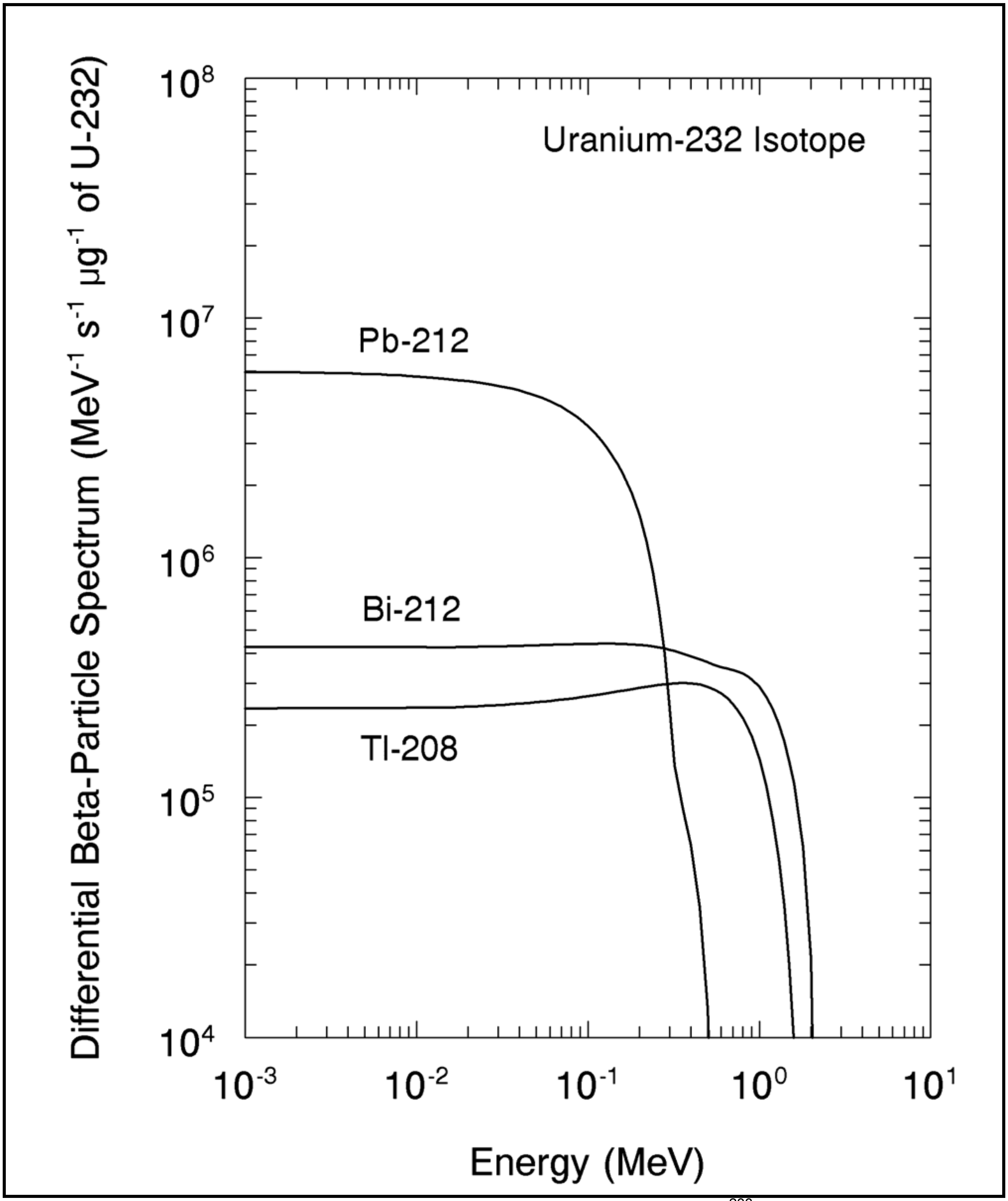

Figure 5-3. Energy spectra of beta particles from the decay products of ^{233}U as calculated using the DEXRAX code of the ICRP38 computer program package (Eckerman 2003). The amount of ^{232}U contaminant in the ^{233}U processed at Y-12 was measured to be 47 ppm (or 47 µg of ^{232}U/g of ^{233}U) and the emission of beta particles per gram of ^{233}U would be 47 times that shown in this figure.

is an uncertainty of ±30 mrem in reading the film badges when the readings are between 0 and 30 mrem. However, the ±30 mrem does not represent the uncertainty when the reading of the film badge is greater than 30 mrem (Morgan 1961). If an exposure was to hard X-rays or gamma rays with energies from 100 keV to 3 MeV, the uncertainty was about ±15% for a dose reading of 100 mrem and ±10% for a dose reading of 1 rem. The uncertainties for beta particles were essentially the same as those for hard X-rays or gamma rays unless there was an exposure to an unknown mixture of soft X-rays, hard X-rays and gamma rays, and beta radiation (Morgan 1961).

Mixtures involving all three types of radiation (beta particles, soft X-rays with energies less than 100 keV, and hard X-rays and gamma-rays with energies between 100 keV and 3 MeV) were extremely rare at the Y-12 Plant (Patterson 1958).

6.0 Y-12 EXTERNAL DOSE DATABASE

6.1 DATA DELIVERED TO THE ORAU CENTER FOR EPIDEMIOLOGIC RESEARCH

Electronic files of data for workers from Y-12 and other Oak Ridge sites were provided from 1978 through the early 1990s to the CER at ORAU. These files contained data for more than 17,000 Y-12 workers and included quarterly summations in mrem for the beta, gamma, and neutron doses. More than 425,000 Y-12 records pertained to the film badge period and were used to develop methods to provide individual doses for unmonitored quarterly periods of employment. Additional details concerning these files can be found in the first report of this series (ORAUT 2005a).

6.2 SUBGROUP DATA FOR REGRESSION ANALYSIS OF BETA DOSES

Data for a subgroup of 182 Y-12 workers provided the basis for the regression analysis to evaluate the time trend in the dose potential from beta particles during the period from 1956 to 1965. The 182 workers in this subgroup were employed in departments where most job tasks involved potential exposure to beta particles and were monitored both before and after 1961. A regression model can be used to describe the temporal pattern of beta dose, and the results can be used to estimate quarterly distributions of beta dose for unmonitored quarters before 1956.

The following procedure was used to select the group of workers who had a total of at least six years of data in departments with a potential for exposure to beta sources. Starting with 426,621 quarterly beta doses for the period from the first quarter (Q1) of 1952 to the fourth quarter (Q4) of 1979:

1. Select all quarterly records for period Q1 1956 to Q4 1962 (n = 59,051).

2. Identify all departments with individuals who were monitored from Q1 1956 to Q4 1960. The assumption is that before 1961 the HP Department selected individuals with potential for beta exposure for monitoring.

3. Select records from Set 1 with department numbers from Set 2 (n = 45,280).

4. Select all workers from Set 3 having at least 24 quarterly film badge records with at least four records after 1961 and at least 20 records before 1961. The resulting group consisted of 182 workers with 4,805 quarterly beta doses.

Using a work history database acquired by ORAU from Y-12 (ORAUT 2005a), all job titles with corresponding dates were obtained for each of the 182 long-term Y-12 workers. Multiple job titles for an individual frequently showed a progression of promotions as workers gained skills and seniority. A recurring example was the progression from machine operator to specialty machinist to machinist and, occasionally, to supervisor of machining. For each individual in each group, the job held during the majority of the period from 1956 through 1960 was selected. This job was classified by type of activity (e.g., machining) and duties (worker, foreman, supervisor, or manager).

Table 6-1 lists the results of the job analysis for the 182 workers in the beta dose regression group. Of these workers, 156 (86%) performed tasks that involved no management or supervisory components. Most of these were machinists, chemical or production operators, and fire or security workers. Another 23 members of this group (13%) held positions with some supervisory tasks such as laboratory, inspection, and production supervisors, fire captains, or foremen. The foremen probably had exposure potential similar to that of their workers, and the supervisors could have had exposures somewhat similar to the workers they supervised. Only three (2%) of the 182 individuals were managers, including shift superintendent and assistant shift superintendents.

Table 6-1. Job activities and duties for 182 long-term Y-12 workers selected for regression analysis of beta doses.

Activity	Duties	Number of workers
Crafts	Foreman	5
Fire and security	Supervisor	5
Fire and security	Worker	16
Inspection	Supervisor	1
Inspection	Worker	9
Laboratory work	Supervisor	4
Laboratory work	Worker	5
Machining	Worker	65
Management	Manager	3
Medical	Worker	1
Production	Foreman	7
Production	Supervisor	1
Production	Worker	43
Production support	Worker	17

Table 6-2 provides a comparison between activities and duties of the subgroups used in the gamma and beta regression analyses of this study. A total of 113 workers were present in both of these subgroups. An HP Report for Q3 1962 indicated that many of the workers with the highest exposures to beta particles and gamma rays at the Y-12 Plant were in the Mechanical Operations and Product Certification Departments (UCNC 1963b). Thus, it was not surprising that 113 of the workers in the gamma and beta regression groups were members of both groups.

7.0 STATISTICAL METHODS

7.1 MAXIMUM LIKELIHOOD ESTIMATES FOR QUARTERLY DATA

The ML methods described in the first report of this series (ORAUT 2005a) and Frome and Watkins (2004) were used to obtain estimates of the lognormal parameters and related summary statistics for the beta film badge doses for each quarter from 1956 to 1965.

Table 6-2. Comparison of job activities and duties for long-term Y-12 workers selected for regression analysis of gamma and beta doses.

Activity	Duties	Number of workers	
		Gamma regression	**Beta regression**
Crafts	Foreman	0	5
Fire and security	Supervisor	5	5
	Worker	14	16
Inspection	Supervisor	1	1
	Worker	6	9
Laboratory work	Supervisor	3	4
	Worker	6	5
Machining	Worker	71	65
Management	Manager	4	3
Medical	Worker	1	1
Production	Supervisor	1	1
	Foreman	4	7
	Worker	28	43
Production support	Worker	2	17
Research and development	Worker	1	0
Total number of workers[a]		**147[b]**	**182[c]**

a. Redundancy of 113 workers between the two subgroups.
b. Selected from workers in the entire population of Y-12 workers.
c. Selected from workers in departments with a potential for exposure to beta particles.

7.2 REGRESSION ANALYSIS AND THE PREDICTION DENSITY

Let d_i denote the radiation dose at time t_i (in years) and assume that the d_i at fixed times t_i ($i = 1,..., n$) are a random sample from a lognormal distribution with log-scale mean [2]:

$$\mu_i = \mu(x_i ; \alpha,\theta) = \log(\alpha + \theta x_i) \tag{7-1}$$

and standard deviation σ. The GSD is exp(σ), and the geometric mean $GM_i = \alpha + \theta x_i$, where $x_i = 1961 - t_i$; i.e., α is the GM in Q1 1961 [3].

The logarithm of the likelihood function for the unknown parameters α, θ, and σ is:

$$L(\alpha,\theta,\sigma) = \Sigma_i \log[g(d_i ; \mu_i,\sigma)] + (n - m)\log [G(d_i^* ; \mu_i,\sigma)] \tag{7-2}$$

where $g(d; \mu,\sigma)$ is the lognormal probability density function and $G(d^*; \mu,\sigma)$ is the lognormal distribution function evaluated at d^* (the detection limit). The summation in Equation 7-2 is over all of the m non-zero d_i. The maximum likelihood estimates (MLEs) of α, θ, and σ and the variance-covariance matrix are obtained numerically with the use of the function **optim()** in the R system (RCDT 2004). Further details on how to obtain and use R are provided in Frome and Watkins (2004).

To estimate the prediction density for an unmonitored quarterly dose $z = \log(d)$ at time t_u the "large sample" ML prediction density proposed by Lejeune and Faulkenberry (1982) is used:

$$q(z; x, \mu) = n[\hat{\mu}(x_u ; \hat{\alpha}, \hat{\theta}), \hat{\sigma}^2 + \mathrm{var}(\hat{\mu}(x_u , \hat{\alpha}, \hat{\theta}))] \tag{7-3}$$

In Equation 7-3, $n[\mu,\sigma^2]$ is the normal density function with mean μ and variance σ^2. For a given quarter t_u, $x_u = (1961 - t_u)$ and $\hat{\mu}(x_u ; \hat{\alpha}, \hat{\theta}) = \log(\hat{\alpha} + \hat{\theta} x_u)$.

The second term in the variance in Equation 7-3 is nonlinear in the parameters. The variance of $\hat{\mu}(x ; \hat{\alpha}, \hat{\theta}) = \log(\hat{\alpha} + \hat{\theta} x)$ can be estimated using the method of statistical differentials (Elandt-Johnson and Johnson 1980); that is:

$$\mathrm{var}(\hat{\mu}(x ; \hat{\alpha}, \hat{\theta})) = p_1^2 \mathrm{var}(\hat{\alpha}) + p_2^2 \mathrm{var}(\hat{\theta}) + 2p_1p_2\mathrm{cov}(\hat{\alpha}, \hat{\theta}) \tag{7-4}$$

In Equation 7-4, $p_1 = \partial\mu/\partial\alpha$ and $p_2 = \partial\mu/\partial\theta$ are evaluated at the MLEs, and $\mathrm{var}(\hat{\alpha})$, $\mathrm{var}(\hat{\theta})$, and $\mathrm{cov}(\hat{\alpha}, \hat{\theta})$ are obtained from the ML variance-covariance matrix.

Because the ML prediction for z = log(d) is normal, it follows that the prediction density for the unknown dose at time t_u is lognormal with GM = $\hat{\alpha} + \hat{\theta}(1961 - t_u)$ and GSD = $\exp(\hat{\sigma})$. In the situation of interest, the second term in the variance is much less than $\hat{\sigma}^2$ and can be ignored for all practical purposes.

7.3 NONPARAMETRIC ANALYSIS USING MODIFIED BOXPLOTS

A modified version of a boxplot was used to summarize the beta film badge doses. For each quarter the Kaplan-Meier (K-M) product limit estimate (PLE) of the empirical distribution function was calculated as described in Frome and Watkins (2004, Section 4.4). A large number of the beta doses were nondetects and recorded as zero. Each dose recorded as zero was treated as a left-censored value at an MDL of 30 mrem. The PLE adjusts for nondetects, which occurred in most of the quarters. A conventional boxplot is obtained by calculating the 25th quartile, xq25, and the 75th quartile, xq75, which define the ends of the box that contain the central 50% of the data. Large outliers for each quarter are identified by calculating the value of xq75 + 1.5 × (xq75 – xq25), and all data points that exceed this value are shown in the boxplot by a separate symbol, such as a +, for each outlier. Small quarterly outliers are identified by calculating xq25 – 1.5 × (xq75 – xq25), and all positive data less than this value are shown separately in the boxplot.

A modified boxplot is obtained by calculating the 25th and 75th quartiles using inverse interpolation from the PLE to take nondetects into account. The modified boxplots in this report show xq25 as a blue inverted triangle and xq75 as a green upright triangle, and the box connecting these quartiles is not drawn. The maximum dose is shown as a red circle, and the minimum dose is a red diamond when no left-censored data were present. Each dose in a quarter that exceeded (on logarithmic scale) log(xq75) + 1.5 × [log(xq75) – log(xq25)] is shown as a black plus sign (+). All data points in a quarter that are less than (on logarithmic scale) log(xq25) – 1.5 × [log(xq75) – log(xq25)] are also shown as plus signs, although these might be incomplete if there were a large number of zero doses. The percent zeros, percent positive outliers, number of film badge readings, and censoring adjusted K-M means are shown as part of the modified boxplots of this report.

8.0 USE OF FILM BADGE MEASUREMENTS TO EVALUATE BETA DOSES OVER TIME

8.1 ALL QUARTERLY BETA DOSES

There were 426,621 beta doses recorded for Y-12 workers from 1952 to 1979 including nondetects recorded as zeros. All summary statistics used to obtain the modified boxplots (Section 7.3) for each quarter are listed in Table 8-1 and shown in Figure 8-1. Figure 8-2 shows additional summary information by quarter in separate plots for the percentage of the quarterly doses that were recorded as zero, the percentage of positive outliers, the total number of quarterly doses, and the quarterly K-M means. Note that when a lognormal distribution is used to describe a quarterly dose distribution, rsdy = [log(xq75) - log(xq25)] ÷ 1.35 provides an outlier-resistant nonparametric estimate of the standard deviation of log(d), which is equivalent to the log(GSD) [4].

In Figures 8-1, 8-3, and 8-5 the horizontal blue line segments mark values of 10% of the RPG, which changed somewhat over this period (Table 8-1), and the vertical blue dashed line at 1961 indicates the time at which all workers were monitored. In Figure 8-1, 75% of the beta doses each quarter were found to be lower than 10% of the RPG except for 1954 to 1958, when some of the quarterly dose 75th percentiles were slightly larger. Beginning in 1961, when monitoring was extended to all workers regardless of exposure potential, there was a precipitous drop in the 75th, 50th, and 25th percentiles of dose, which indicated that the newly monitored workers generally had doses far lower than the workers who were selected to be monitored before 1961. Maximum quarterly doses remained fairly constant from 1953 to 1970, which verified that workers with the highest exposure potential were already being monitored before 1961. Dose distributions from 1961 and later were highly skewed toward very low doses, which pulled the boundary for outliers to much lower values and resulted in additional high outliers. These outliers can be seen in the long stretches of black crosses beginning in 1961 when monitoring for all workers began. The number of film badge readings on which each quarterly boxplot was based, shown in Figure 8-2, was generally about 1,000 or less before 1961 and about 5,000 or more afterwards.

The following nonparametric summary statistics were calculated and are listed in Table 8-1:

kmm = K-M estimate of the mean for the quarter.
kmse = the K-M estimate of the standard error of the K-M mean.
xqp = pth quartile, p = 25, 50, 75 (xq50 is an estimate of the GM).
xmax = the maximum dose in quarter.
rsdy = [log(xq75) - log(xq25)] ÷ 1.35 = estimate of log(GSD).
cdose is cumulative dose (or sum of all doses).
pnd = percent nondetects.
cdosea = n*kmm = "adjusted" cumulative dose.
nout = number of positive outliers.
n = total number of quarterly doses.

The adjusted cumulative dose is an estimate of the total dose adjusted for nondetects (zero doses), and is obtained by multiplying the K-M mean by the number of doses (i.e., cdosea = n*kmm). An estimate of missed dose (for monitored workers) is obtained by subtracting the cumulative dose from the adjusted cumulative dose.

To further investigate the suitability of fitting lognormal models to the quarterly beta exposure data after 1956, q-q plots and R-square statistics were produced for each quarter, as shown in Attachment A. With few exceptions, R-square was well above 0.9 for quarters in 1956 and later, but it was much lower in earlier years.

Table 8-1. PLE summary statistics for Y-12 quarterly beta doses, 1952 to 1979.

Quarter	kmm	kmse	xq25	xq50	xq75	xmax	rsdy	cdose	cdosea	pnd	nout	n
52	115.0	14.0	10.7	21.3	118.0	1,530	1.783	19,347	23,690	70.4	0	206
52.25	345.2	43.2	10.2	20.4	102.0	3,780	1.707	81,755	87,336	73.5	1	253
52.5	247.7	26.7	9.5	19.1	28.6	2,625	0.814	69,033	76,292	78.6	64	308
52.75	220.1	26.8	9.0	18.0	27.0	2,988	0.814	75,317	84,959	83.4	56	386
53	381.1	71.3	9.0	18.1	27.1	4,605	0.814	52,360	56,022	83.0	24	147
53.25	334.8	62.3	8.9	17.8	26.8	3,712	0.814	48,604	52,564	84.1	25	157
53.5	418.9	57.2	11.0	22.0	436.2	2,750	2.729	60,160	63,254	68.2	0	151
53.75	413.3	31.0	21.8	291.1	510.8	3,989	2.339	134,586	138,042	34.4	0	334
54	411.3	40.4	29.3	227.4	294.5	4,615	1.711	133,986	136,552	25.6	0	332
54.25	717.6	77.8	19.0	266.5	841.3	6,961	2.811	144,686	147,108	39.5	0	205
54.5	771.0	72.3	20.5	585.0	898.0	5,892	2.803	153,518	155,742	36.6	0	202
54.75	968.3	45.6	247.9	613.8	1,318.0	5,311	1.238	479,014	481,245	15.1	0	497
55	986.3	42.8	399.6	655.5	1,132.5	7,046	0.772	516,922	517,808	5.7	3	525
55.25	816.5	32.7	197.1	723.9	978.7	5,065	1.188	426,285	428,662	15.0	0	525
55.5	629.0	32.5	238.4	494.0	657.0	4,439	0.751	291,540	294,372	20.1	8	468
55.75	1,102.9	63.0	499.5	815.0	1,242.0	8,522	0.675	438,953	438,954	20.4	12	398
56	861.5	33.7	426.0	651.0	1,038.0	4,470	0.660	385,636	385,952	4.5	1	448
56.25	681.8	32.5	195.0	447.0	832.0	3,828	1.075	335,407	335,446	0.2	0	492
56.5	745.3	28.0	319.8	495.0	917.0	4,419	0.781	459,847	459,850	0.2	0	617
56.75	557.1	25.3	216.0	338.0	600.0	5,234	0.757	345,393	345,402	0.3	12	620
57	975.2	37.9	471.9	688.5	1,098.8	9,524	0.627	550,937	550,988	0.4	7	565
57.25	682.1	25.3	234.9	432.0	921.0	3,393	1.013	405,847	405,850	0.2	0	595
57.5	517.0	20.6	193.1	299.0	664.0	3,621	0.916	345,365	345,356	0.1	0	668
57.75	475.1	17.1	194.7	303.5	569.4	3,028	0.796	322,130	322,118	0.0	1	678
58	465.9	16.2	194.7	282.0	619.0	3,017	0.858	327,976	327,994	0.0	0	704
58.25	322.4	15.3	66.5	198.0	408.0	3,674	1.345	223,153	223,746	4.8	0	694
58.5	413.7	15.0	154.5	307.0	549.9	3,084	0.941	284,655	285,039	3.2	0	689
58.75	318.0	11.8	61.2	204.5	470.0	2,755	1.511	249,632	250,584	7.9	0	788
59	289.7	10.8	54.2	182.0	422.0	2,245	1.521	242,922	244,507	9.2	0	844
59.25	304.1	11.4	64.8	201.0	425.5	2,532	1.395	259,124	259,701	4.4	0	854
59.5	369.6	18.8	57.6	203.6	471.0	5,956	1.558	334,555	335,966	8.9	0	909
59.75	373.4	18.7	45.9	177.5	485.8	10,407	1.749	391,002	393,190	12.3	0	1,053
60	279.7	12.6	32.0	108.0	354.0	5,109	1.782	319,784	321,096	6.0	0	1,148
60.25	391.6	17.7	44.8	165.3	468.0	5,910	1.739	431,590	432,326	3.9	0	1,104
60.5	464.6	18.9	55.4	230.8	590.3	3,840	1.753	489,680	490,153	2.7	0	1,055
60.75	398.5	17.2	49.4	177.5	518.2	3,628	1.742	392,300	392,522	1.4	0	985
61	125.0	4.0	11.3	22.9	86.8	4,475	1.512	625,940	662,625	45.8	29	5,301
61.25	112.9	4.0	4.9	14.0	58.0	4,379	1.828	600,191	623,772	39.8	17	5,525
61.5	101.4	3.3	7.5	15.4	59.5	4,069	1.531	550,282	557,092	10.9	41	5,494
61.75	94.1	3.4	5.6	13.8	51.6	4,534	1.651	495,874	523,666	46.4	42	5,565
62	92.2	2.9	7.8	18.3	63.8	2,555	1.560	494,696	514,753	30.0	28	5,583
62.25	136.6	4.8	10.6	24.2	78.9	4,266	1.490	717,376	731,083	19.5	87	5,352
62.5	112.7	3.5	15.9	24.4	64.2	2,986	1.036	567,228	607,904	43.5	343	5,394
62.75	84.8	3.1	12.4	21.9	28.6	3,700	0.618	392,191	451,730	68.0	793	5,327
63	80.6	3.0	17.3	24.3	36.4	4,800	0.550	374,051	439,754	62.0	736	5,456
63.25	70.7	2.6	1.8	9.4	30.8	2,519	2.108	363,997	391,395	59.3	4	5,536
63.5	95.4	3.4	17.2	23.6	56.7	5,825	0.886	485,017	529,375	42.3	380	5,549
63.75	66.8	2.2	9.9	18.1	47.3	3,047	1.161	329,266	364,795	48.2	122	5,461
64	73.3	2.5	14.1	19.2	40.2	4,054	0.777	350,941	401,464	58.3	484	5,477
64.25	83.9	2.6	18.2	24.5	60.7	3,368	0.891	399,539	445,845	43.9	249	5,314
64.5	91.7	3.1	16.2	27.1	51.1	3,034	0.853	482,032	491,512	10.6	417	5,360
64.75	76.6	3.4	11.0	16.9	26.1	3,810	0.644	329,985	392,345	78.1	633	5,122
65	58.8	2.0	7.4	15.8	27.7	3,424	0.976	252,975	296,176	62.3	379	5,037
65.25	61.3	2.5	8.7	15.6	36.4	2,924	1.056	258,853	274,256	27.6	197	4,474
65.5	51.9	2.6	6.4	12.8	26.6	5,290	1.059	209,635	225,506	29.6	223	4,345
65.75	43.3	1.8	9.1	16.5	25.4	2,726	0.756	144,097	187,749	68.9	317	4,336
66	64.3	2.9	10.5	20.5	41.4	5,290	1.019	269,756	278,612	13.8	158	4,333

Quarter	kmm	kmse	xq25	xq50	xq75	xmax	rsdy	cdose	cdosea	pnd	nout	n
66.25	63.2	2.8	9.1	18.6	35.6	5,290	1.012	260,308	274,225	23.7	223	4,339
66.5	72.2	3.2	10.5	21.6	50.8	5,290	1.173	297,393	317,680	32.1	95	4,400
66.75	63.5	2.2	10.0	23.0	39.4	1,894	1.017	270,808	284,798	19.4	192	4,485
67	57.8	2.4	11.1	16.9	38.9	5,290	0.929	237,292	260,967	37.9	203	4,515
67.25	64.3	2.6	9.5	19.9	43.4	5,290	1.127	279,823	296,616	25.7	139	4,613
67.5	42.0	1.9	5.3	12.2	25.0	5,290	1.142	161,328	199,626	67.9	174	4,753
67.75	50.8	2.0	6.2	15.2	31.4	5,290	1.202	219,480	243,688	42.4	143	4,797
68	55.0	2.6	5.7	13.5	27.8	5,290	1.180	239,455	268,620	52.3	200	4,884
68.25	28.6	1.5	5.4	10.6	20.7	5,290	0.995	100,474	142,256	74.9	183	4,974
68.5	48.1	1.7	7.9	16.0	27.3	2,663	0.916	196,730	250,697	73.8	336	5,212
68.75	49.8	1.8	7.9	15.6	26.4	2,932	0.896	206,283	263,591	74.9	394	5,293
69	36.1	1.2	5.9	13.6	24.3	1,162	1.046	142,308	194,868	75.7	245	5,398
69.25	37.7	1.7	6.0	11.8	22.5	3,986	0.977	168,895	206,068	58.1	280	5,466
69.5	31.7	1.8	4.1	9.9	19.4	5,290	1.148	135,328	188,140	80.9	196	5,935
69.75	30.8	1.8	2.8	8.7	15.4	4,660	1.264	148,342	181,166	64.1	187	5,882
70	40.3	2.9	3.1	7.2	17.5	8,120	1.283	202,042	242,767	76.5	213	6,024
70.25	18.7	0.7	3.0	7.2	15.1	1,514	1.202	82,310	112,237	57.9	96	6,002
70.5	47.1	2.5	5.4	11.4	20.1	7,200	0.982	250,084	306,574	77.7	474	6,509
70.75	54.3	2.5	4.6	13.1	24.4	5,492	1.238	317,080	362,290	57.7	297	6,672
71	31.9	1.4	5.6	11.5	21.2	1,961	0.987	137,896	215,612	90.7	303	6,759
71.25	29.2	1.0	3.9	7.9	17.0	1,647	1.102	161,979	197,304	53.9	301	6,757
71.5	18.6	0.9	3.7	7.1	15.4	1,462	1.060	64,122	123,299	92.8	172	6,629
71.75	19.0	0.8	3.0	5.6	13.3	1,354	1.112	84,144	124,564	78.2	217	6,556
72	26.0	1.4	2.8	6.6	15.3	3,675	1.257	134,384	169,650	65.9	182	6,525
72.25	43.1	1.3	6.6	14.6	26.3	3,330	1.021	227,823	275,840	60.0	305	6,400
72.5	29.3	0.9	7.6	15.7	24.3	1,071	0.862	106,216	187,608	86.0	254	6,403
72.75	33.4	1.1	7.4	14.3	25.4	1,151	0.920	133,502	206,880	83.2	291	6,194
73	31.9	1.0	6.1	13.5	21.9	1,019	0.943	134,159	201,321	83.5	308	6,311
73.25	35.9	1.4	9.2	16.1	23.9	2,542	0.710	140,266	217,626	85.1	356	6,062
73.5	26.3	1.0	4.7	10.9	21.9	1,872	1.134	93,431	154,644	85.8	129	5,880
73.75	24.7	1.1	6.9	14.0	20.6	1,158	0.811	62,573	133,331	92.1	190	5,398
74	41.7	2.0	5.6	13.0	22.6	2,210	1.037	155,407	220,927	89.6	252	5,298
74.25	34.2	1.3	6.0	14.3	23.5	1,350	1.005	124,507	183,278	82.0	230	5,359
74.5	29.1	1.1	6.2	13.5	21.4	1,231	0.922	96,214	156,092	84.9	221	5,364
74.75	27.8	1.2	5.9	13.5	23.1	2,145	1.018	81,935	144,949	88.6	162	5,214
75	34.1	1.2	5.6	14.4	25.1	1,281	1.118	122,052	176,229	79.8	123	5,168
75.25	36.8	1.3	5.1	12.7	24.0	1,207	1.148	138,448	180,946	72.9	133	4,917
75.5	30.8	1.2	4.9	11.9	24.5	1,953	1.189	101,723	138,076	70.7	67	4,483
75.75	32.2	1.1	4.8	12.0	24.6	1,624	1.217	112,104	146,188	66.2	67	4,540
76	51.6	1.1	24.3	38.5	47.7	1,730	0.501	235,526	238,289	4.4	273	4,618
76.25	22.1	1.0	4.5	11.2	20.4	1,655	1.125	67,747	101,770	66.3	54	4,605
76.5	24.9	1.1	4.0	9.1	17.0	1,555	1.079	86,799	113,843	59.4	134	4,572
76.75	25.8	1.1	6.2	14.5	22.4	1,670	0.950	66,632	121,105	84.5	108	4,694
77	20.4	0.8	3.4	8.5	17.8	1,206	1.221	68,629	100,633	65.9	56	4,933
77.25	15.3	0.4	4.3	9.5	18.2	1,553	1.062	45,505	76,821	59.4	1	5,021
77.5	28.7	1.2	6.2	11.7	19.9	2,300	0.861	120,537	145,165	43.0	251	5,058
77.75	21.7	0.9	3.1	7.3	16.9	1,383	1.246	78,504	106,373	62.0	63	4,902
78	26.2	1.0	4.4	10.2	19.2	1,433	1.096	109,993	131,183	40.7	132	5,007
78.25	27.6	1.2	3.5	8.5	18.5	1,673	1.245	116,223	140,015	50.2	110	5,073
78.5	27.7	1.4	4.8	10.7	19.0	1,708	1.022	90,346	144,095	89.0	169	5,202
78.75	25.9	1.1	3.7	9.1	20.7	1,660	1.287	107,413	136,104	55.9	56	5,255
79	30.0	1.0	5.6	12.8	23.5	1,638	1.064	123,970	155,070	51.9	110	5,169
79.25	41.9	1.2	7.7	17.7	34.9	1,587	1.119	214,347	230,953	23.2	90	5,512
79.5	27.7	1.1	5.9	11.8	21.8	1,621	0.969	99,901	143,929	70.4	151	5,196
79.75	39.6	1.5	5.9	13.7	24.9	1,622	1.072	177,670	217,364	59.0	183	5,489

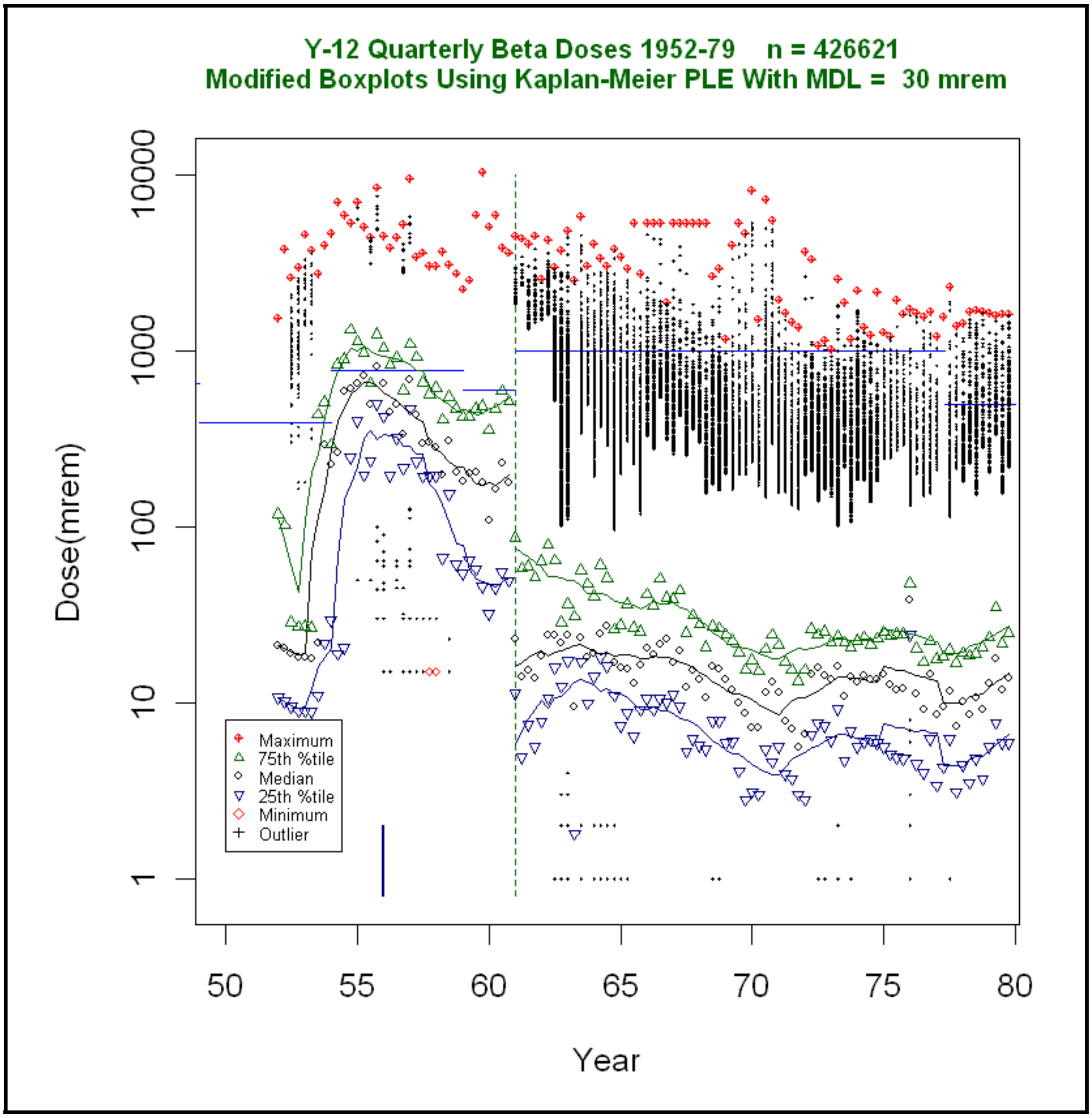

Figure 8-1. Modified boxplots of Y-12 quarterly beta doses using Kaplan-Meier product limit estimate.

8.2 QUARTERLY BETA DOSES FOR TWO LARGE Y-12 DEPARTMENTS

To verify further that individuals selected for monitoring before 1961 were the workers with exposure potential, two departments were examined. The Y-12 department with the largest number of quarterly beta doses after 1961 was Department 2014 (Buildings, Grounds, and Maintenance Shops). This department had only 39 beta doses recorded before 1961 and 32 of these doses were zero. Of interest were the quarterly beta dose distributions after 1961 when all members of this department were monitored. Figure 8-3 shows the modified quarterly boxplots and demonstrates that all but 6 of the 19,435 beta doses were below 10% of the RPG. In addition, 60% or more of the beta doses were zero for most quarters, as shown in Figure 8-4. In contrast, Department 2073 (Process Design and Engineering) had the largest number of beta doses recorded before 1961. Figure 8-5 shows there was essentially no change in the 75th, 50th, and 25th percentiles of the beta doses in 1961 when all workers were

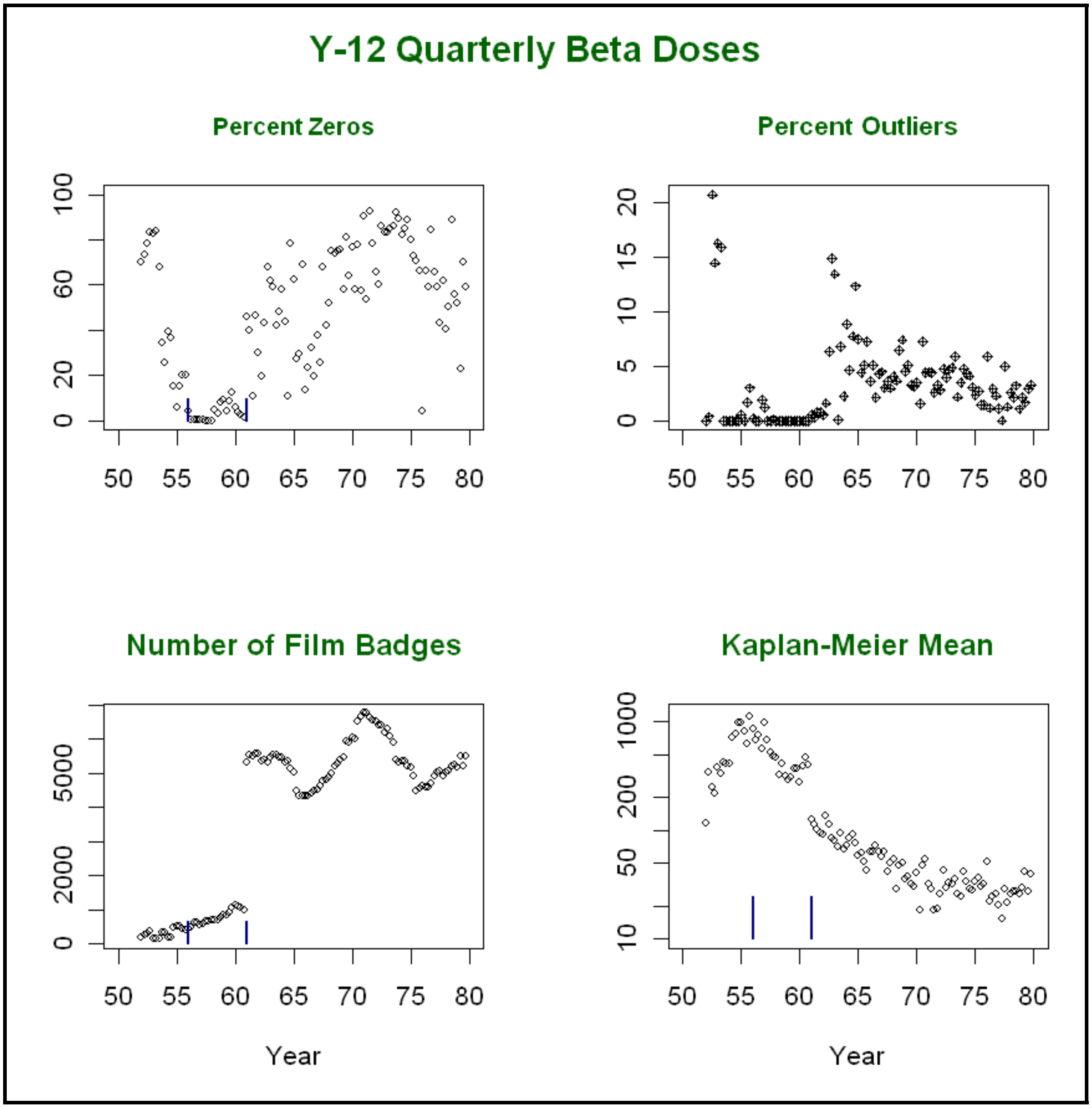

Figure 8-2. Related summary statistics for Y-12 quarterly beta doses, 1952 to 1979.

monitored (compare with Figure 8-1), with the 75th percentile generally about 750 mrem. Only after 1970 when the percent of zero doses increased dramatically, as shown in Figure 8-6, did the beta dose distributions drop.

8.3 Limitations of Doses for Dose Reconstruction

After reviewing the boxplot in Figure 8-1 and the q-q plots and R-square statistics in Attachment A, as well as the monitoring and recording practices during the film badge period, it was decided that a lognormal model could be used with quarterly dose data after Q1 1956 for estimating the prediction density for the dose reconstruction procedure described in ORAUT (2004a). Quarterly data for beta doses before this date were found not to fit lognormal or other commonly used statistical distributions. The reasons for the lack of fit before Q1 1956 appear to be (1) the small size of the monitored worker

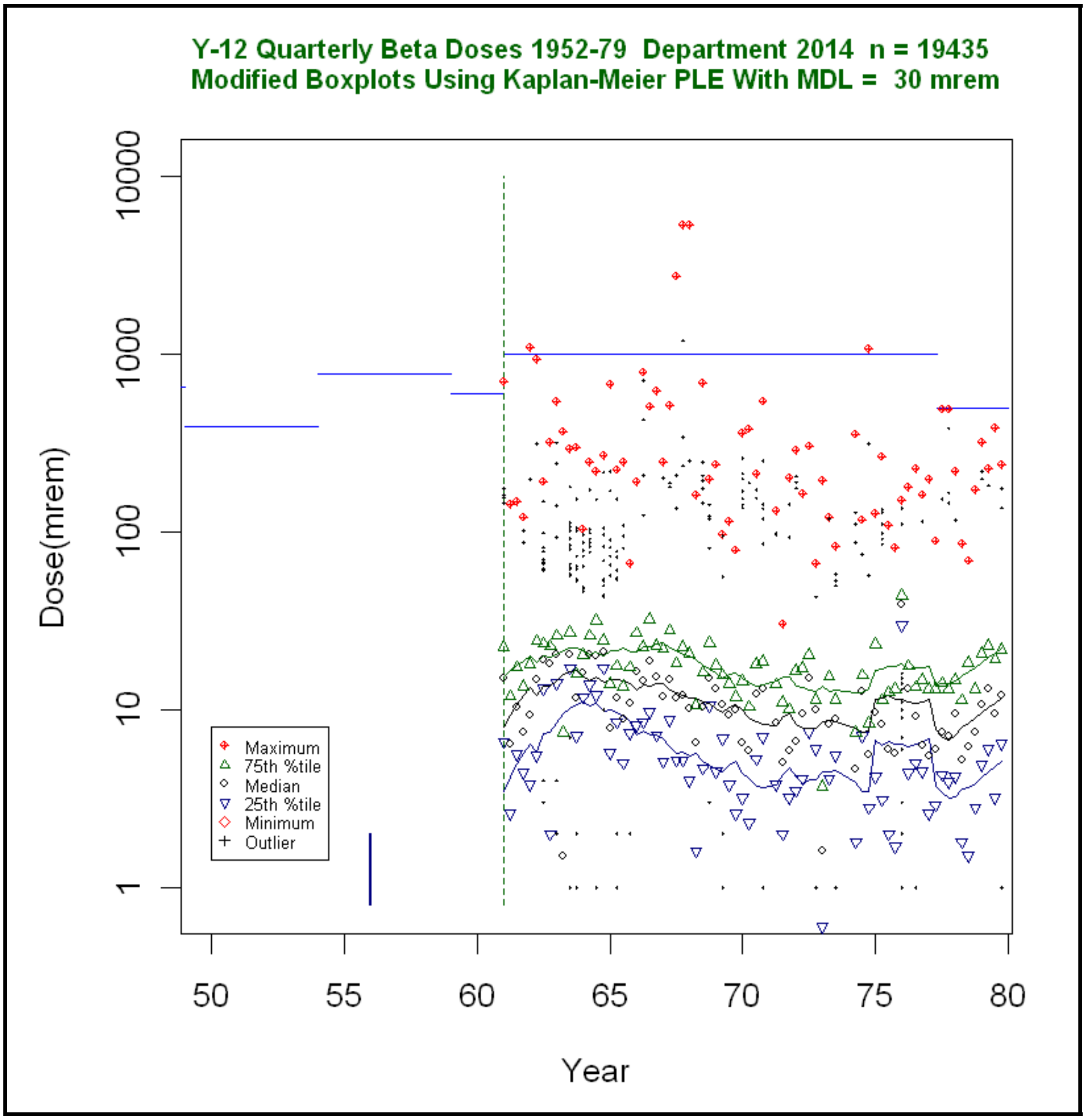

Figure 8-3. Modified boxplots of Department 2014 quarterly beta doses.

populations, (2) the frequent exchange of the film badge dosimeters, and (3) the methods of assigning dose if the measured beta-particle dose was less than the MDL of the film badge dosimeter.

Certain summary statistics were investigated and further confirmed the suitability of using the lognormal model and data for a quarter if the unmonitored dose occurred during or after 1956. Table 8-2 lists these summary statistics, most of which were based on application of a lognormal model to each set of quarterly film badge data beginning with 1956. The logarithmic scale mean (column *mu* in Table 8-2), standard deviation (column *sig*), and standard error of the mean (column *se.mu*) can be used to determine the parameters of a lognormal prediction density for an individual who was not monitored during a quarter [5].

The five-fold jump between 1960 and 1961 in the number of doses per quarter corroborates the policy change from monitoring selected workers with higher exposure potential to monitoring all workers. In

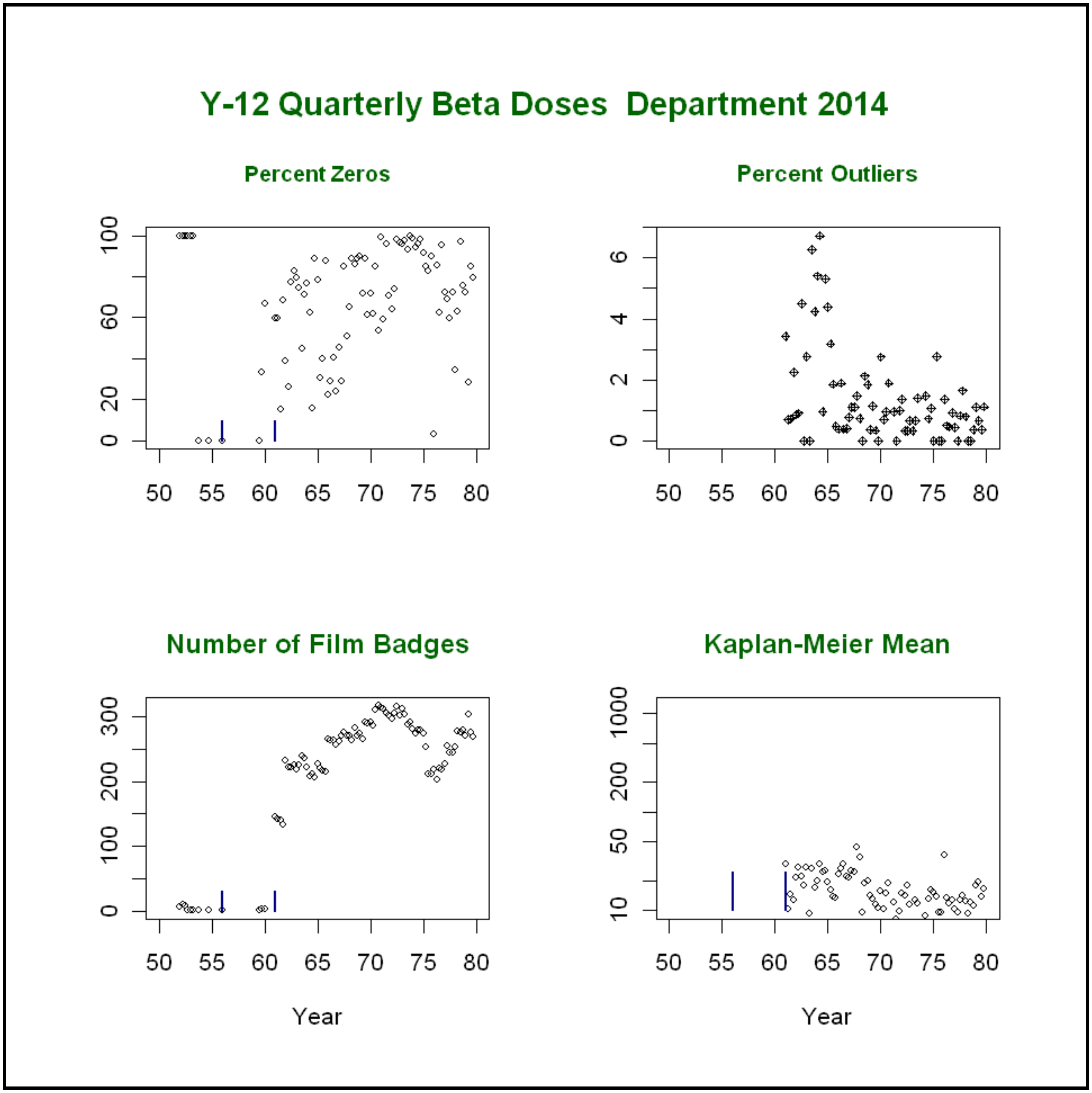

Figure 8-4. Related summary statistics for Department 2014 quarterly beta doses.

addition, the inclusion of workers with lower exposure potential led to a generally higher percentage of nondetectable quarterly doses, although this percentage varied substantially from quarter to quarter.

As expected, beginning in 1961 the estimates of mean, median, 99th-percentile, and upper tolerance limits dropped substantially from earlier years because the population of monitored workers was no longer restricted to individuals with higher exposure potential. Before 1961 (the period with numerous unmonitored quarters), the expected dose derived from the quarterly lognormal model (column AM in Table 8-2) was generally higher than the mean dose estimated nonparametrically using the K-M product limit method (column KM in Table 8-2). In addition, from Q1 1956 through 1960, the 99–95

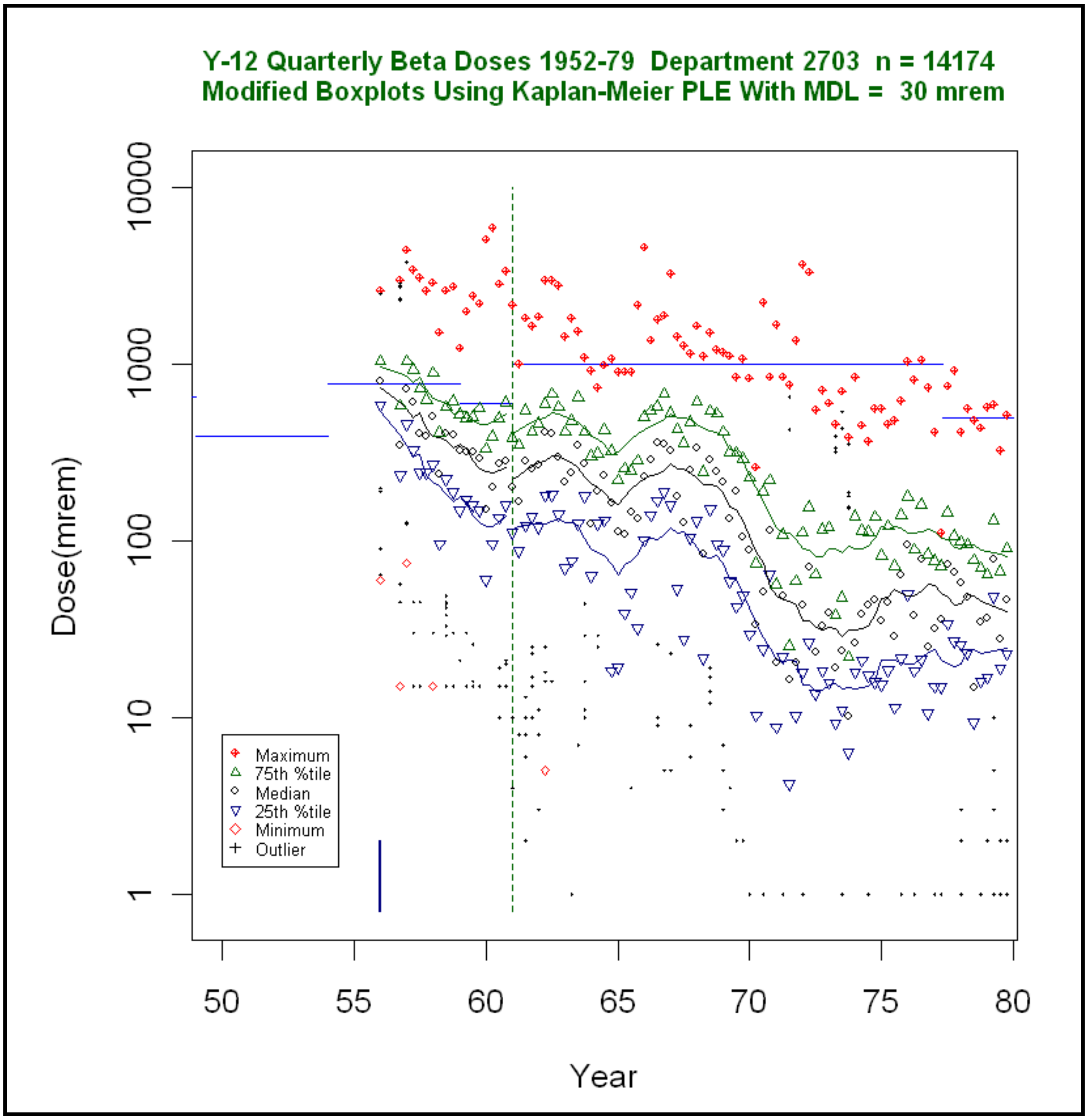

Figure 8-5. Modified boxplots of Department 2703 quarterly beta doses.

geometric upper tolerance limit (column UTL) based on the lognormal model generally exceeded the nonparametric 99–95 geometric upper tolerance limit (column NPUTL). These findings support the use of the model-based approach because it would likely result in estimated doses that were somewhat higher and therefore favorable to claimants. The final column in Table 8-2 represents the radiation protection guideline in effect during a given quarter (Section 3.1).

A comparison of the upper tolerance limits to the RPG demonstrates compliance with the guidelines in force during this period.

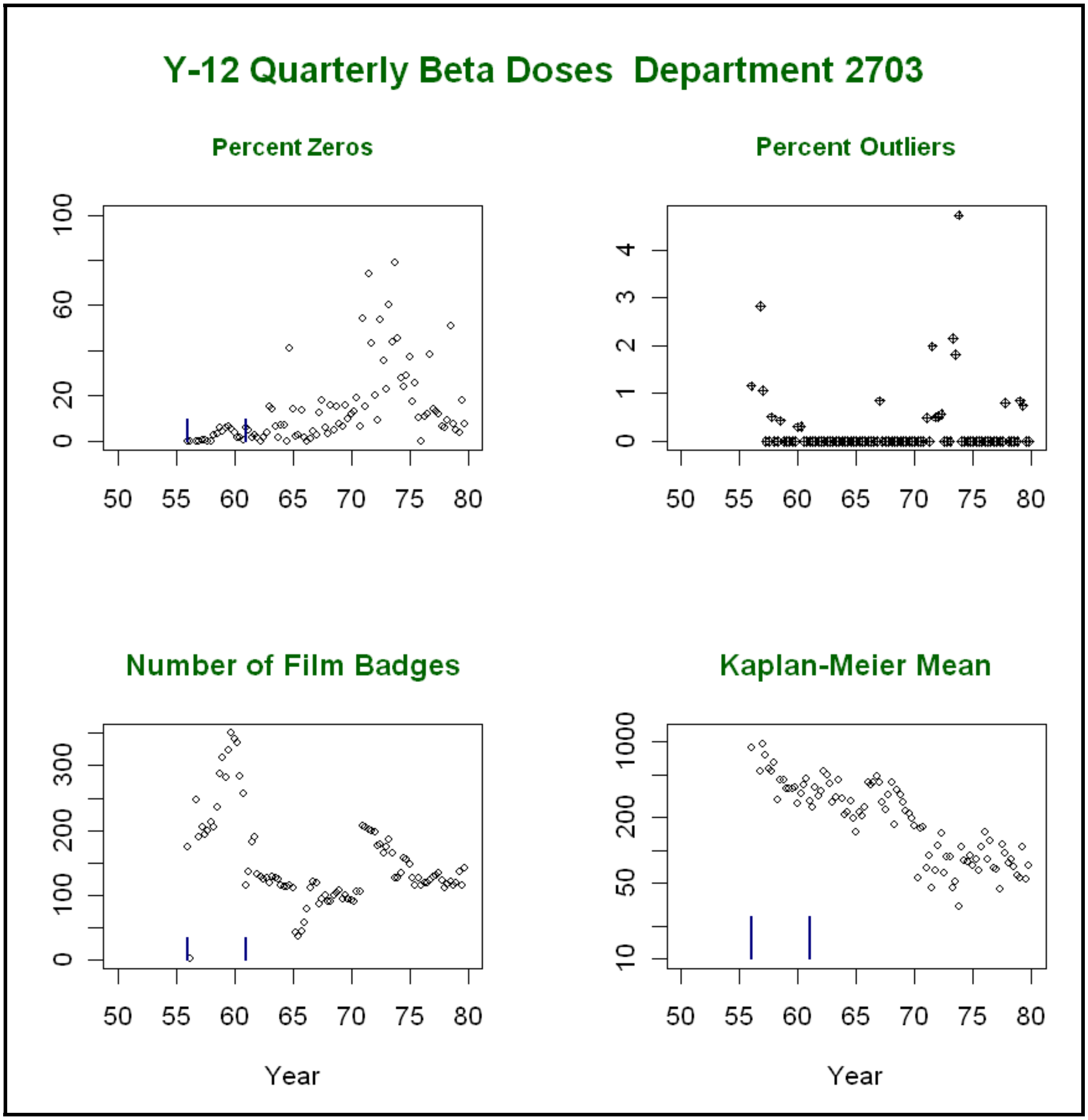

Figure 8-6. Related summary statistics for Department 2703 quarterly beta doses.

9.0 ESTIMATES FOR UNMONITORED QUARTERLY BETA DOSES

9.1 PROCEDURE USED THROUGH FOURTH QUARTER OF 1955

As discussed in Section 8.2, information gathered from the boxplots and q-q plots led to the determination that quarterly dose datasets before Q1 1956 were not suitable for estimating doses for unmonitored quarters during this period. An alternative approach was developed in which the parameters of a lognormal prediction density were estimated from a regression analysis based on the subgroup data of 182 workers (Section 6.2) who had higher dose exposure potential than the workers who were not monitored.

Table 8-2. MLE summary statistics for Y-12 quarterly beta doses, 1956 to 1965.

Yr	Qtr	N	%ND	mu	sig	se.mu	GM	KM	AM	D99	UTL	NPUTL	RPG
56	1	448	4	6.334	1.141	0.054	563	861	1,080	8,011	9,541	4,470	7,800
56	2	492	0	5.891	1.314	0.059	362	682	858	7,690	9,281	3,727	7,800
56	3	617	0	6.245	0.894	0.036	516	745	769	4,130	4,630	3,933	7,800
56	4	620	0	5.881	0.968	0.039	358	557	572	3,406	3,854	4,042	7,800
57	1	565	0	6.564	0.842	0.035	709	975	1,010	5,024	5,622	5,829	7,800
57	2	595	0	6.145	0.906	0.037	467	682	703	3,835	4,315	3,338	7,800
57	3	668	0	5.814	0.976	0.038	335	517	540	3,247	3,661	3,396	7,800
57	4	678	0	5.834	0.794	0.031	342	475	468	2,168	2,389	2,606	7,800
58	1	704	0	5.803	0.839	0.032	331	466	471	2,335	2,582	2,507	7,800
58	2	694	5	5.149	1.200	0.046	172	322	354	2,811	3,257	2,628	7,800
58	3	689	3	5.527	1.147	0.044	251	414	486	3,628	4,175	2,501	7,800
58	4	788	8	5.094	1.323	0.047	163	318	391	3,542	4,132	1,671	7,800
59	1	844	9	4.984	1.320	0.046	146	290	349	3,148	3,654	1,795	6,000
59	2	854	4	5.086	1.252	0.043	162	304	354	2,979	3,420	1,756	6,000
59	3	909	9	5.119	1.378	0.046	167	370	432	4,129	4,796	4,450	6,000
59	4	1,053	12	4.983	1.519	0.047	146	373	462	4,996	5,834	3,330	6,000
60	1	1,148	6	4.739	1.390	0.041	114	280	300	2,898	3,308	2,385	6,000
60	2	1,104	4	5.021	1.479	0.045	152	392	453	4,735	5,462	3,186	6,000
60	3	1,055	3	5.235	1.503	0.046	188	465	581	6,203	7,193	3,156	6,000
60	4	985	1	5.147	1.368	0.044	172	398	438	4,144	4,761	3,124	6,000
61	1	5,301	46	3.219	1.812	0.030	25	125	129	1,694	1,855	1,561	10,000
61	2	5,525	40	2.909	1.878	0.029	18	113	107	1,447	1,580	1,706	10,000
61	3	5,494	11	3.198	1.563	0.022	24	101	83	929	995	1,295	10,000
61	4	5,565	46	2.811	1.840	0.030	17	94	90	1,200	1,310	1,414	10,000
62	1	5,583	30	3.081	1.665	0.024	22	92	87	1,048	1,129	1,239	10,000
62	2	5,352	20	3.414	1.656	0.024	30	137	120	1,434	1,545	2,128	10,000
62	3	5,394	43	3.114	1.783	0.029	23	113	110	1,425	1,554	1,375	10,000
62	4	5,327	68	2.154	2.215	0.050	9	85	100	1,491	1,686	1,258	10,000
63	1	5,456	62	2.725	1.759	0.035	15	81	72	912	1,003	1,150	10,000
63	2	5,536	59	2.240	2.088	0.039	9	71	83	1,210	1,343	1,134	10,000
63	3	5,549	42	3.231	1.492	0.023	25	95	77	814	874	1,204	10,000
63	4	5,461	48	2.869	1.571	0.026	18	67	61	681	735	795	10,000
64	1	5,477	58	2.785	1.651	0.031	16	73	63	754	821	963	10,000
64	2	5,314	44	3.276	1.412	0.023	26	84	72	707	758	1,101	10,000
64	3	5,360	11	3.457	1.292	0.018	32	92	73	641	679	1,234	10,000
64	4	5,122	78	1.354	2.638	0.082	4	77	126	1,790	2,111	1,429	10,000
65	1	5,037	62	2.581	1.662	0.034	13	59	53	631	691	760	10,000
65	2	4,474	28	2.863	1.456	0.024	18	61	51	518	556	887	10,000
65	3	4,345	30	2.829	1.277	0.021	17	52	38	330	352	719	10,000
65	4	4,336	69	2.309	1.562	0.039	10	43	34	381	418	636	10,000

The regression analysis of the group of 182 workers described in Section 6.2 is based on the assumption that the doses follow a lognormal distribution with logarithmic scale mean $\mu_i = \log[\alpha + \theta(1961 - t_i)]$ and standard deviation σ (Section 7.2). Zero doses are treated as censored at 30 mrem. The ML estimates of the regression parameters and their standard errors are listed in Table 9-1. The $\mathrm{cov}(\hat{\alpha}, \hat{\theta})$ is equal to 2.297.

Table 9-1. MLEs of regression parameters.

	α	θ	σ
Estimate	151.71	56.83	1.345
Standard error	3.04	1.82	0.014

The results of the regression analysis can be used to estimate the lognormal parameters for the prediction density for beta doses for quarters when a worker was not monitored before 1956. For example, for Q2 1950 the MLE of the GM is:

$$GM_{1950.25} = 151.71 + 56.83[1961 - t_i] = 151.71 + 56.83[1961 - 1950.25] = 762.3 \text{ mrem}$$

The arithmetic mean and the 95th percentile in mrem for this quarter are:

$$\begin{aligned} mean_{1950.25} &= \exp[\log(762.3) + (1.345^2 / 2)] \\ &= \exp[6.636 + 0.905] = 1884 \end{aligned}$$

$$\begin{aligned} xq95_{1950.25} &= \exp[(\log(762.3) + z_{.95} \times 1.345] \\ &= \exp[6.636 + (1.645 \times 1.345)] = 6968 \end{aligned}$$

The results in Table 9-2 for quarters from 1947 through 1955 were determined by the procedure discussed in this section.

Figure 9-1 shows boxplots for each quarter from 1956 to 1962 based on the set of 4,805 data points used for the regression approach. The solid line from upper left to lower right shows the median dose for each quarter determined by the MLEs obtained by fitting a lognormal model for left-censored data with zero doses replaced by a value of 30 mrem for the MDL. Figure 9-1 shows a general trend of decreasing beta dose with increasing time.

9.2 PROCEDURE USED AFTER FOURTH QUARTER OF 1955

Exploratory data analysis showed that it was reasonable to fit lognormal models to the actual quarterly dose data beginning with Q1 1956 (Sections 8.2 and 8.3). The period before 1961 was of particular interest because unmonitored quarters after 1961 were rare [6]. Lognormal parameters were calculated from each quarterly dose dataset using ML methods for left-censored data as described in Section 7.1. These parameters were used to determine separate lognormal prediction densities that could be sampled to estimate dose for a worker's unmonitored quarter. The ML prediction density in any quarter for z = log(d) is normal with mean $\hat{\mu}$ and $\hat{\sigma} = [\hat{\sigma}^2 + \text{var}(\hat{\mu})]^{1/2}$. Values of $\hat{\mu}$, $\hat{\sigma}$, and $\text{var}(\hat{\mu})$ can be determined from columns 5 to 7 [μ, σ, and se(μ)] in Table 8-2. For easier implementation in dose reconstruction, the quantity $[\hat{\sigma}^2 + \text{var}(\hat{\mu})]^{1/2}$ was calculated for each quarter and appears in column 4 (sig) of Table 9-2, and the GSD in column 6 is the corresponding exp(sig).

The results in Table 9-2 for quarters from 1956 through 1965 were determined by the procedure discussed in this section.

Table 9-2. Parameters for lognormal prediction density, 1947 to 1965.

Year	Qtr	mu	sig	GM	GSD	Edose
1947	3	6.8231	1.3687	918.82	3.9304	2,344.4
1947	4	6.8075	1.3687	904.61	3.9304	2,308.2
1948	1	6.7917	1.3687	890.41	3.9304	2,272.0
1948	2	6.7756	1.3687	876.20	3.9304	2,235.7
1948	3	6.7593	1.3687	862.00	3.9304	2,199.5
1948	4	6.7426	1.3687	847.79	3.9304	2,163.2
1949	1	6.7257	1.3687	833.59	3.9304	2,127.0
1949	2	6.7085	1.3687	819.38	3.9304	2,090.7
1949	3	6.6911	1.3687	805.17	3.9304	2,054.5
1949	4	6.6733	1.3687	790.97	3.9304	2,018.2
1950	1	6.6551	1.3687	776.76	3.9304	1,982.0
1950	2	6.6367	1.3687	762.56	3.9304	1,945.7
1950	3	6.6179	1.3687	748.35	3.9304	1,909.5
1950	4	6.5987	1.3687	734.15	3.9304	1,873.2
1951	1	6.5792	1.3687	719.94	3.9304	1,837.0
1951	2	6.5592	1.3687	705.73	3.9304	1,800.7
1951	3	6.5389	1.3687	691.53	3.9304	1,764.5
1951	4	6.5181	1.3687	677.32	3.9304	1,728.2
1952	1	6.4970	1.3687	663.12	3.9304	1,692.0
1952	2	6.4753	1.3687	648.91	3.9304	1,655.7
1952	3	6.4532	1.3687	634.71	3.9304	1,619.5
1952	4	6.4305	1.3687	620.50	3.9304	1,583.3
1953	1	6.4074	1.3687	606.29	3.9304	1,547.0
1953	2	6.3837	1.3687	592.09	3.9304	1,510.8
1953	3	6.3594	1.3687	577.88	3.9304	1,474.5
1953	4	6.3345	1.3687	563.68	3.9304	1,438.3
1954	1	6.3090	1.3687	549.47	3.9304	1,402.0
1954	2	6.2828	1.3687	535.27	3.9304	1,365.8
1954	3	6.2559	1.3687	521.06	3.9304	1,329.5
1954	4	6.2282	1.3687	506.85	3.9304	1,293.3
1955	1	6.1998	1.3687	492.65	3.9304	1,257.0
1955	2	6.1705	1.3687	478.44	3.9304	1,220.8
1955	3	6.1404	1.3687	464.24	3.9304	1,184.5
1955	4	6.1093	1.3687	450.03	3.9304	1,148.3
1956	1	6.3333	1.1410	563.00	3.1299	1,079.5
1956	2	5.8916	1.3140	362.00	3.7210	858.3
1956	3	6.2461	0.8940	516.00	2.4449	769.5
1956	4	5.8805	0.9680	358.00	2.6327	571.9
1957	1	6.5639	0.8420	709.00	2.3210	1,010.6
1957	2	6.1463	0.9060	467.00	2.4744	704.0
1957	3	5.8141	0.9760	335.00	2.6538	539.4
1957	4	5.8348	0.7940	342.00	2.2122	468.7
1958	1	5.8021	0.8390	331.00	2.3141	470.6
1958	2	5.1475	1.2000	172.00	3.3201	353.4

Year	Qtr	mu	sig	GM	GSD	Edose
1958	3	5.5255	1.1470	251.00	3.1487	484.6
1958	4	5.0938	1.3230	163.00	3.7547	391.1
1959	1	4.9836	1.3200	146.00	3.7434	348.9
1959	2	5.0876	1.2520	162.00	3.4973	354.7
1959	3	5.1180	1.3780	167.00	3.9670	431.6
1959	4	4.9836	1.5190	146.00	4.5677	462.8
1960	1	4.7362	1.3900	114.00	4.0149	299.5
1960	2	5.0239	1.4790	152.00	4.3886	453.8
1960	3	5.2364	1.5030	188.00	4.4952	581.7
1960	4	5.1475	1.3680	172.00	3.9275	438.4
1961	1	3.2189	1.8120	25.00	6.1227	129.1
1961	2	2.8904	1.8780	18.00	6.5404	105.0
1961	3	3.1781	1.5630	24.00	4.7731	81.4
1961	4	2.8332	1.8400	17.00	6.2965	92.4
1962	1	3.0910	1.6650	22.00	5.2857	88.0
1962	2	3.4012	1.6560	30.00	5.2383	118.2
1962	3	3.1355	1.7830	23.00	5.9477	112.7
1962	4	2.1972	2.2150	9.00	9.1614	104.6
1963	1	2.7081	1.7590	15.00	5.8066	70.5
1963	2	2.1972	2.0880	9.00	8.0688	79.6
1963	3	3.2189	1.4920	25.00	4.4460	76.1
1963	4	2.8904	1.5710	18.00	4.8115	61.8
1964	1	2.7726	1.6510	16.00	5.2122	62.5
1964	2	3.2581	1.4120	26.00	4.1042	70.5
1964	3	3.4657	1.2920	32.00	3.6401	73.7
1964	4	1.3863	2.6380	4.00	13.9852	129.8
1965	1	2.5649	1.6620	13.00	5.2698	51.7
1965	2	2.8904	1.4560	18.00	4.2888	52.0
1965	3	2.8332	1.2770	17.00	3.5859	38.4
1965	4	2.3026	1.5620	10.00	4.7683	33.9

9.3 PARAMETERS FOR LOGNORMAL PREDICTION DENSITIES

Columns 5 and 6 in Table 9-2 contain the GM and GSD of each quarterly lognormal prediction density, which can be used to estimate a dose for an unmonitored quarter. Table 9-2 covers the years from the management takeover of Y-12 by UCCND in 1947 to 1965. The GMs and GSDs for the earlier and later years were obtained in two distinct manners. The values for 1947 through 1955 were calculated using the subgroup regression approach discussed in Section 9.1. In contrast, from Q1 1956 through 1965, the GM and GSD for each quarter were determined by applying a lognormal model directly to the doses for that quarter, as discussed in Section 9.2.

9.4 SCALING PROCEDURE BASED ON MAXIMUM LIKELIHOOD METHOD

The scaling procedure developed for gamma doses can be used to estimate beta doses for workers not monitored in quarters before 1961. ORAUT (2004a) provides a detailed derivation and explanation of the scaling procedure, and ORAUT (2004b) illustrates its use for gamma doses.

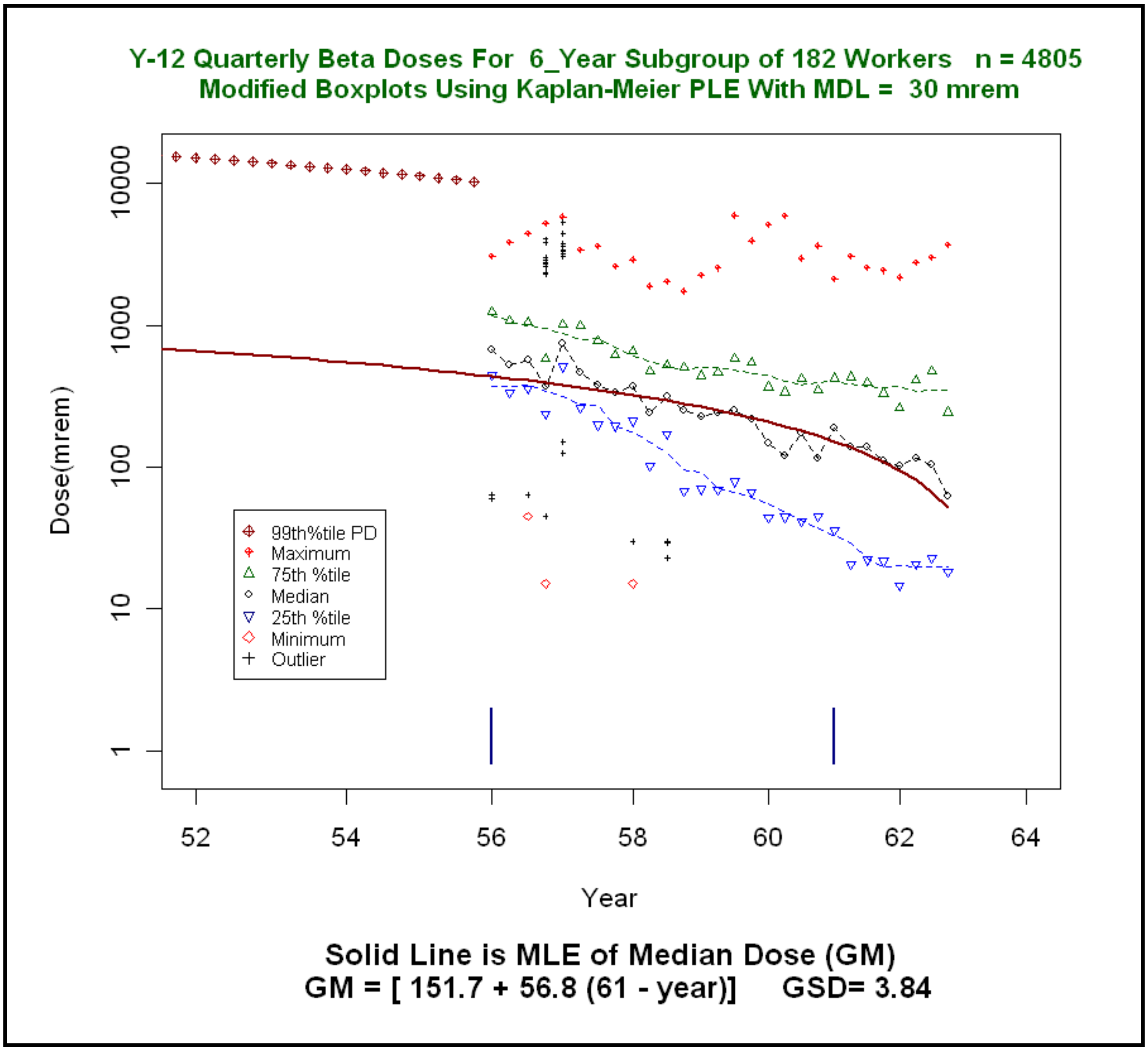

Figure 9-1. Quarterly doses for a subgroup of 182 workers used for regression analysis.

If a Y-12 worker was employed for at least five quarters from 1961 to 1965, that individual's monitoring data can be used to adjust the dose distributions for unmonitored quarters from 1947 through 1960 [7]. The method is based on the assumption that the individual's potential for exposure from 1947 to 1961 was similar to that from 1961 to 1965, that the individual's doses differed from the population dose by a constant factor, and that the missed dose in an unmonitored quarter can be described by a lognormal distribution. The adjustment is applied only if the calculated scaling factor is greater than 1, which will increase the value of the expected quarterly dose.

Suppose that d_t is the recorded dose during quarter t and that μ_t and σ_t are the known lognormal parameter values for that same quarter, which lies between Q1 1961 and Q4 1965 (Table 9-2, columns 3 and 4). Therefore, $y_t = \log(d_t)$ follows the normal distribution with mean $\mu_t + \varphi$, and standard deviation σ_t, where φ represents the average relative difference (on the logarithmic scale) of the individual's doses from the population values. The MLE of φ is $\hat{\varphi} = \Sigma_t w_t v_t / \Sigma_t w_t$, where $w_t = 1/\sigma_t^2$ and $v_t = y_t - \mu_t$. The variance of $\varphi = [\Sigma_t w_t]^{-1}$. If for any quarter $d_t = 0$ (indicating a nondetect), replace y_t with y_t^o, the conditional expectation of y given it is less than the log(MDL). To obtain y_t^o, first calculate $z_t = [\log(\text{MDL}) - \mu_t] \div \sigma_t$ and then $y_t^o = \mu_t - [n(z_t)/N(z_t)]\,\sigma_t$, where n(z) is the standard normal density and N(z) is the standard normal cumulative distribution function (Johnson, Kotz, and Balakrishnan 1995, Section 10.1). Table 9-3 lists the values of μ, σ, w, and y^o (based on a value of 30 mrem for MDL).

Table 9-3. Calculation of scaling factor for Section 9.4 example.

Year	Qtr	mu	sig	w	y^0	d	y	v
1961	1	3.219	1.812	0.305	1.887	30	3.401	0.182
1961	2	2.890	1.878	0.284	1.701	185	5.220	2.330
1961	3	3.178	1.563	0.409	2.069	155	5.043	1.865
1961	4	2.833	1.840	0.295	1.707	245	5.501	2.668
1962	1	3.091	1.665	0.361	1.953	108	4.682	1.591
1962	2	3.401	1.656	0.365	2.080	220	5.394	1.992
1962	3	3.135	1.783	0.315	1.878	115	4.745	1.609
1962	4	2.197	2.215	0.204	1.118	128	4.852	2.655
1963	1	2.708	1.759	0.323	1.714	80	4.382	1.674
1963	2	2.197	2.088	0.229	1.215	130	4.868	2.670
1963	3	3.219	1.492	0.449	2.142	0	2.142	-1.077
1963	4	2.890	1.571	0.405	1.943	165	5.106	2.216
1964	1	2.773	1.651	0.367	1.828	0	1.828	-0.945
1964	2	3.258	1.412	0.502	2.221	118	4.771	1.513
1964	3	3.466	1.292	0.599	2.393	0	2.393	-1.072
1964	4	1.386	2.638	0.144	0.375	20	2.996	1.609
1965	1	2.565	1.662	0.362	1.721	125	4.828	2.263
1965	2	2.890	1.456	0.472	2.033	42	3.738	0.847
1965	3	2.833	1.277	0.613	2.146	62	4.127	1.294
1965	4	2.303	1.562	0.410	1.662	58	4.060	1.758

Example

Consider a worker with recorded dose d_t for each quarter from 1961 to 1965 as listed in column 8 of Table 9-3. The calculated values of y_t and v_t are in columns 9 and 10 of Table 9-3 so that:

$$\hat{\varphi} = \Sigma_t\, w_t v_t / \Sigma_t\, w_t = 1.20312$$

and

$$\text{var}(\hat{\varphi}) = 1/\Sigma_t\, w_t = 0.13492$$

Note that the values in columns 4 to 7 of Table 9-3 are the same for each worker, whereas the values in columns 8 to 10 are determined by the individual recorded beta doses for each quarter of employment from 1961 through 1965.

9.5 APPLICATION OF THE SCALING PROCEDURE

Let t indicate a quarter for which a dose distribution is required for a worker unmonitored between January 1947 and December 1960. Without scaling, the unmonitored dose is lognormal with parameters (on the logarithmic scale) μ_t and σ_t (from Table 9-2); that is, $y_t = \log(d_t)$ is normally distributed with mean μ_t and standard deviation σ_t. The mean and standard deviation of the adjusted logarithmic dose are:

$$\mu_t^* = \mu_t + \hat{\varphi}$$

and

$$\sigma_t^* = [\sigma_t^2 + \text{var}(\hat{\varphi})]^{1/2};$$

that is, the unmonitored dose in quarter t is lognormal with mean μ_t^* and standard deviation σ_t^*. If a worker was unmonitored for all four quarters in a given year, the adjusted lognormal parameters are calculated for each quarter and the annual dose estimate is obtained by Monte Carlo sampling as described in ORAUT (2004a).

Example (continued)

To estimate the unmonitored dose in Q1 1957 for the worker in this example, use

$$\hat{\varphi} = 1.20312 \text{ and var}(\hat{\varphi}) = 0.13492$$

from above, so that

$$\mu_t^* = 6.5639 + 1.20312 = 7.767$$

and

$$\sigma_t^* = [0.842^2 + 0.13492]^{1/2} = 0.9186$$

where $\mu_t = 6.5639$ and $\sigma_t = 0.842$ are obtained from line 57 of Table 9-2. The unmonitored dose for the quarter is lognormal with $\mu_t^* = 7.767$ and $\sigma_t^* = 0.9186$. The adjusted GM is $\exp(\mu_t^*) = 2361$ and the adjusted GSD is $\exp(\sigma_t^*) = 2.506$.

9.6 EXAMPLES OF APPLICATION OF REGRESSION MODEL AND SCALING PROCEDURE

Figures 9-2 through 9-5 provide examples of applying the beta regression model values and scaling procedure to obtain quarterly doses for workers with limited beta monitoring data before 1961. As discussed in Section 9.4, the scaling procedure can be used for workers who had unmonitored quarters before 1961 but have at least five quarters of monitoring data from 1961 through 1965. The scaling procedure is based on the assumptions that the individual's potential for exposure during the 1950s was similar to that from 1961 to 1965, and that the individual's doses differed from the population dose by a constant factor. If the scaling factor is less than unity (1), the scaling factor is set equal to 1 and the monitored population dose distributions are applied to that worker before 1961.

Comparison of results from the regression and scaling with actual doses received by these workers before 1961 demonstrates in these figures that the doses are regularly favorable to claimants.

Figure 9-5 is used for demonstration only because this worker had different job activities that involved much lower dose potential after 1961. Even in this extreme situation, except for one quarter the GMs assigned by the regression values were higher than the actual GMs, even without scaling upwards.

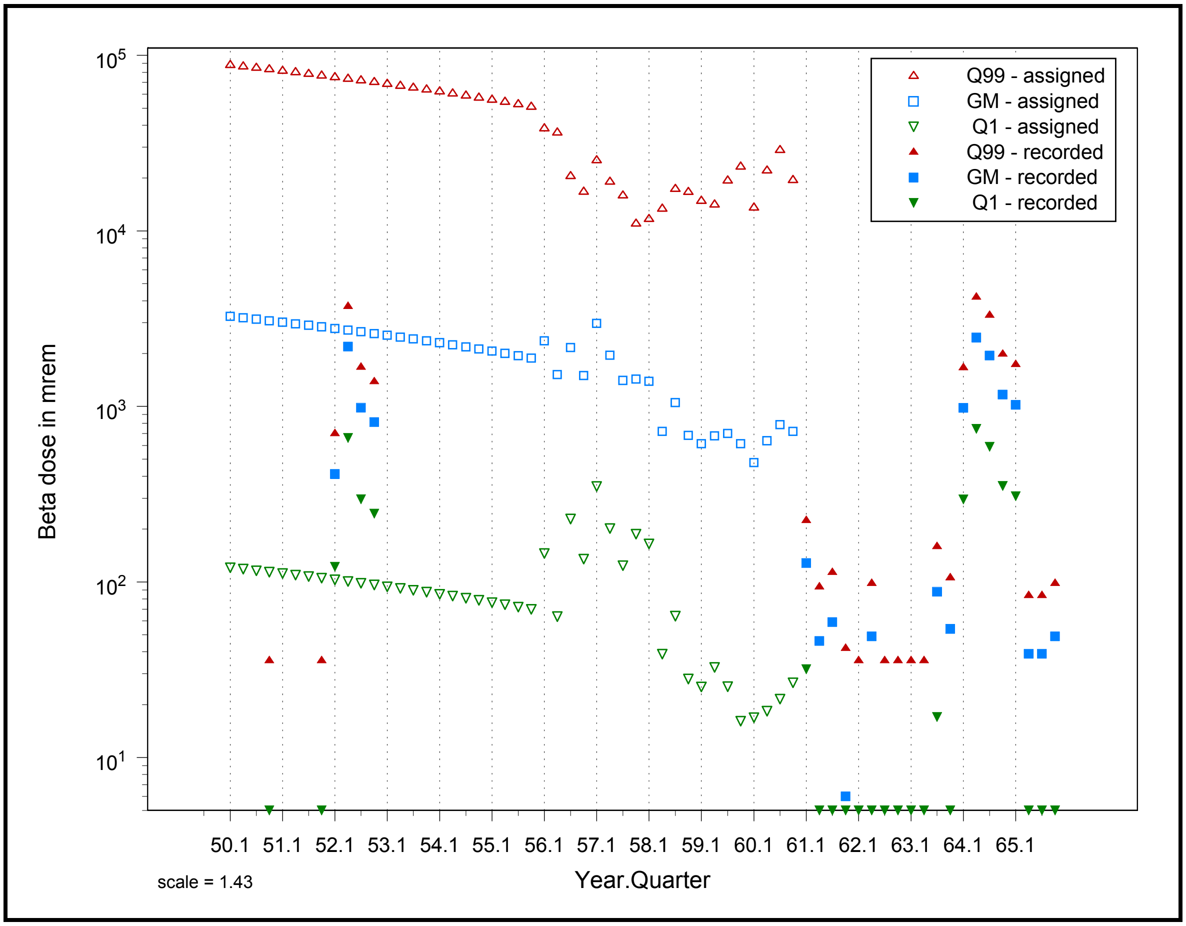

Figure 9-2. Distribution of scaled prediction density versus actual monitored beta doses for a worker with very early doses and a wide dose range. The scaling factor is 1.43 on a logarithmic scale and 4.18 on the original linear scale.

10.0 DISCUSSION

This TIB provides background information on the Y-12 external dosimetry program through 1979 related to the film badge monitoring of beta radiation and sources of beta radiation exposure at the Y-12 Plant. The report also provides comprehensive information on beta doses to Y-12 workers during the film badge period. In addition, the report presents the statistical methods that were developed to provide prediction densities for the sampling of individual doses to a worker during quarters when the worker was employed but not monitored for exposure to beta particles.

The statistical methods reported here include nonparametric modified boxplots for summarizing by quarter more than 425,000 individual beta doses and the derivation of ML quarterly lognormal prediction densities. For 1956 and later years, the doses for each quarter were used to derive parameter estimates by ML methods. For years before 1956, the prediction density parameters were derived by ML regression based on data from a subgroup of 182 workers. These subgroup members were required to have worked for at least 24 quarters from 1956 through 1965 in departments that were monitored during that time. Quarterly GMs and GSDs and summary statistics based on both the nonparametric product limit estimates and MLEs are also provided.

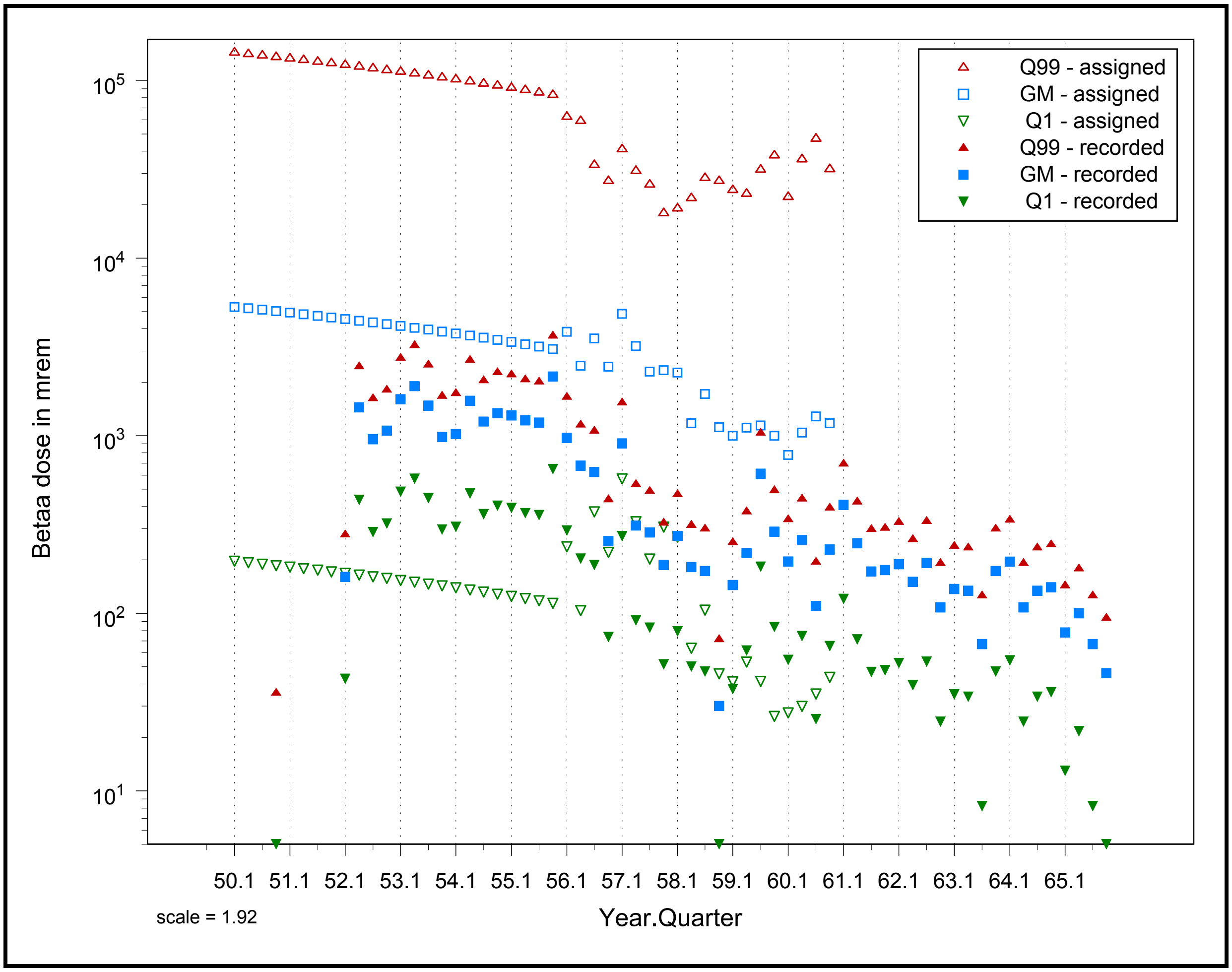

Figure 9-3. Distribution of scaled prediction density versus actual monitored beta doses for a worker with many early doses. The scaling factor is 1.92 on a logarithmic scale and 6.82 on the original linear scale.

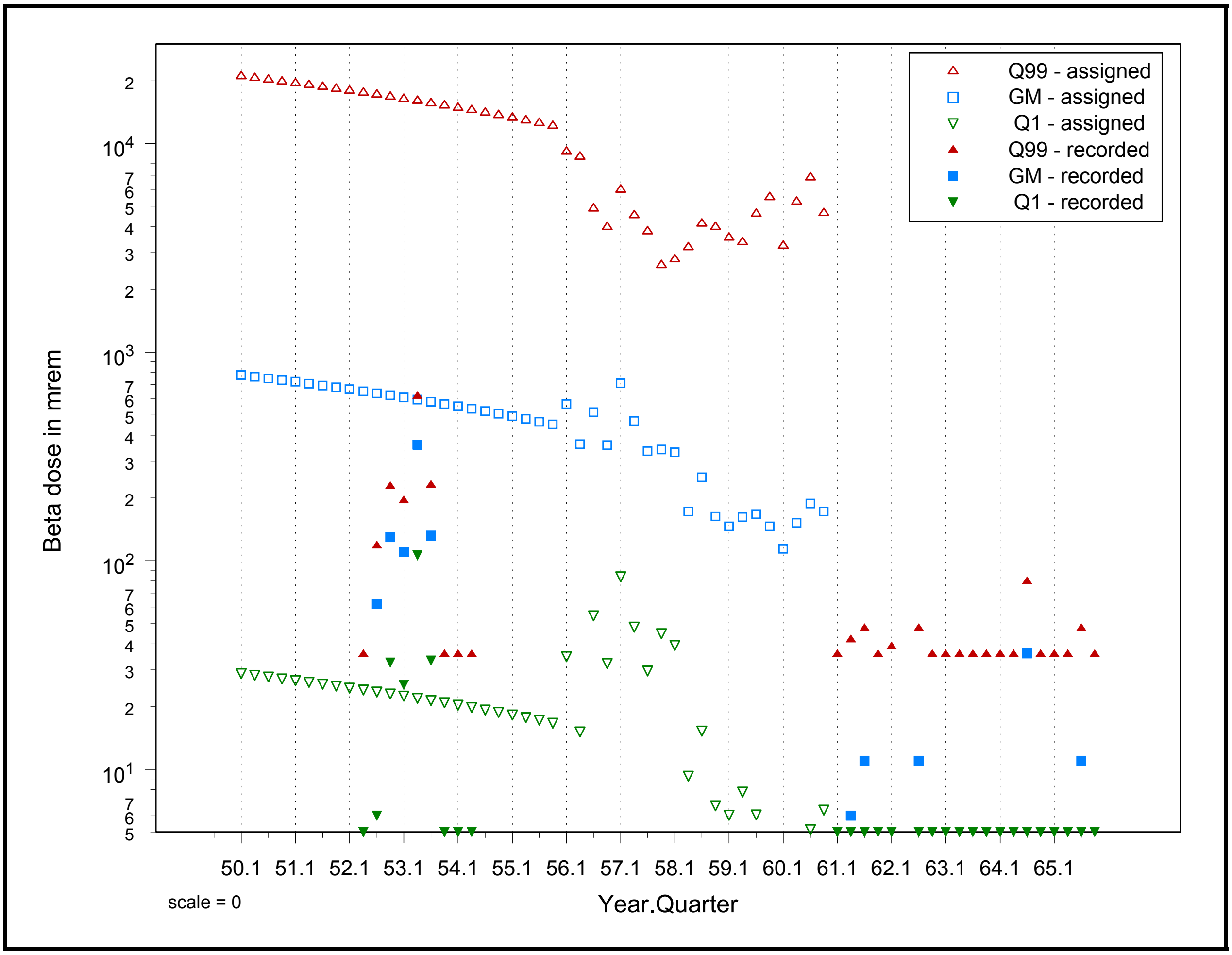

Figure 9-4. Distribution of scaled prediction density versus actual monitored beta doses for a worker with low doses after 1961. The scaling factor is zero on a logarithmic scale and 1.00 on the original linear scale.

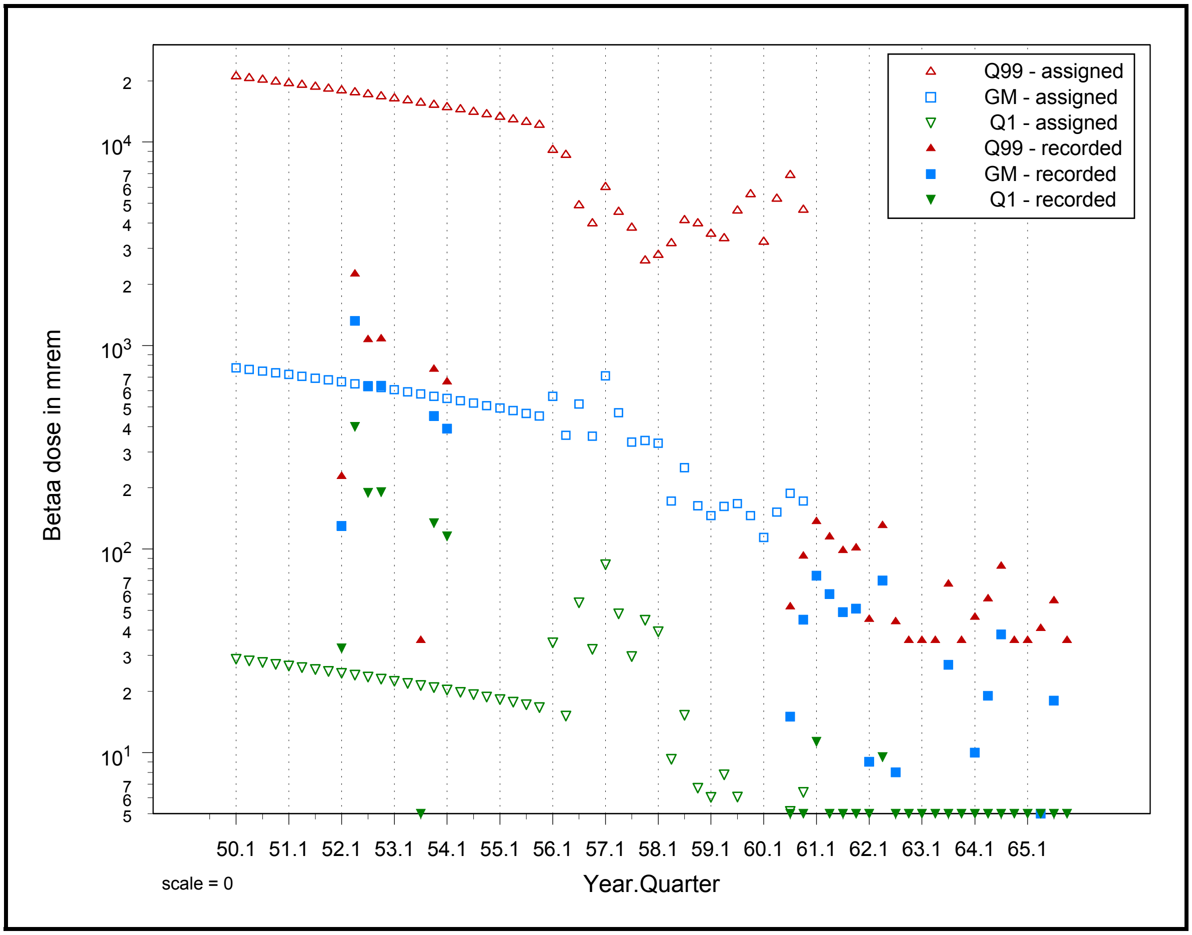

Figure 9-5. Distribution of scaled prediction density versus actual monitored beta doses for a worker with different job activities before and after 1961. The scaling factor is zero on a logarithimic scale and 1.00 on original linear scale.

11.0 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database.

[1] Kerr, George D. ORAU Team. Health Physicist. April 2007.
The film badge doses provided by most DOE facilities in response to EEOICPA requests by NIOSH are the shallow and deep doses as calculated using Equations 3-1 and 3-2. These also appear to be the doses of record at the Y-12 facility from 1950 to 1952. The film badge doses recorded by the Y-12 facility after 1952 clearly include the dose components from beta particles and soft X-rays, gamma rays and hard X-rays, and neutrons. Hence, it is possible in our studies to investigate the doses to Y-12 workers using the separate dose components rather than the sums of the dose components that are provided by the shallow (or skin) and deep (or penetrating whole-body) doses.

[2] Kerr, George D. ORAU Team. Health Physicist. April 2007.
A capital or upper case D is normally used as the symbol for radiation dose. It is typical in statistics, however, to use a lower case letter to represent a variable. Hence, a lower case d is used as the symbol for radiation dose throughout the statistical discussions and statistical sections of this report.

[3] Kerr, George D. ORAU Team. Health Physicist. April 2007.
The regression analysis used for beta doses in this report is different than that used for gamma doses in ORAUT 2005a. The regression analysis for gamma doses is based on a logarithmic dose function and the regression analysis for beta doses is based on a linear dose function. Hence, the GM for the gamma dose (ORAUT 2005a) is equal to exp[3.628 + 0.122(1961 - t)] and the GM for the beta dose (Section 9.1) is equal to 151.7 + 56.8(1961- t) where t is the quarter for which a dose distribution is required for a worker unmonitored from January 1947 to December 1960. As examples, the t for the first quarter of 1954 would be 1954.0 and the t for the second quarter of 1954 would be 1954.25. These two different assumptions were used because a more marked reduction was noted in the time trend for gamma doses prior to 1961 than the time trend for the beta doses. The results of our regression analysis for gamma and beta doses also provide other dose distribution parameters that are needed to calculate the GSDs and so forth.

[4] Watkins, Janice P. ORAU Team. Biostatistician. April 2007.
Since the logs of the beta doses are assumed to follow a Normal distribution, the 75th percentile corresponds to an approximate z-score of 0.675 and the 25th percentile to a z-score of -0.675. The distance [log(xq75) – log(xq25)] is approximately [0.675 – (-0.675)] or 1.35 standard deviations. An estimate of one standard deviation, therefore, would be [log(xq75) – log(xq250] ÷ 1.35.

[5] Watkins, Janice P. ORAU Team. Biostatistician. April 2007.
When the doses, d, follow a lognormal distribution, the ML prediction density in any quarter for z = log(d) is normal with mean $\hat{\mu}$ and $\hat{\sigma} = [\hat{\sigma}^2 + \mathrm{var}(\hat{\mu})]^{1/2}$, where $\hat{\mu}$, $\hat{\sigma}$, and var($\hat{\mu}$) appear in Table 8.2 and are designated as mu, sig, and se.mu.

[6] Kerr, George D. ORAU Team. Health Physicist. April 2007.
Before 1961, film badge dosimeters were not issued to all workers, and there were a lot of unmonitored quarters among workers because film badges were typically provided only to workers who entered certain areas within the Y-12 Plant. In 1961, a new policy was instituted that required all Y-12 workers to be monitored for external radiation exposure with film badges, which were an integral part of the worker's identification badges and contained components for both routine and accident-related dosimetry. Thus, unmonitored quarters among Y-12 workers were rare after 1961.

[7] Watkins, Janice P. ORAU Team. Biostatistician. April 2007.
As an additional assurance that an assigned dose for an unmonitored quarter would be favorable to claimants, a scaling procedure was developed that produced upward adjustment of a quarterly dose whenever there was evidence after complete monitoring began that the worker had higher potential exposure than average. Assigned doses were not scaled downward when evidence showed that the worker appeared to have lower potential than average. The procedure works by scaling the GM and GSD of the lognormal distribution which the dose reconstructor would use as a basis for creating the assigned dose.

REFERENCES

Ashley, J. C., J. E. Turner, M. L. Souleyrette, R. S. Bogard, and K. L. McMahan, 1995, *A Technical Study of TLD Beta Calibration Factor for Exposure to Depleted Uranium*, Y/DQ-59, Lockheed Martin Energy Systems, Y-12 Plant, Oak Ridge, Tennessee, June. [SRDB Ref ID: 16474]

Auxier, J. A., 1967, “Special Methods in Radiation Dosimetry,” *Principles of Radiation Protection,* K. Z. Morgan and J. E. Turner, editors, John Wiley & Sons, New York, New York, pp. 215–241.

Ballenger, H. F., W. H. Baumann, M. B. Long, D. H. Reed, E. C. Long, C. M. West, L. C. Emerson, R. O. Wollan, D. M. Ross, S. R. Bernard, and J. C. Gallimore, 1953, *Health Physics Progress Report, January 1, 1952 to July 1, 1952*, Y-940, Y-12 Plant, Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee, March 17. [SRDB Ref ID: 12503]

Beck, W. J., 1981, “Corrections to 1954 Y-12 Film Badge Data,” memorandum to D. Hudson, Oak Ridge Associated Universities, Oak Ridge, Tennessee, December 9. [SRDB Ref ID: 28125]

Berger, M. J., J. S. Coursey, M. A. Zucker, and J. Chang, 2005, *ESTAR, PSTAR, and ASTAR: Computer Programs for Calculating Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions* (version 1.2.3), NISTIR 4999, National Institute of Standards and Technology, Gaithersburg, Maryland. [SRDB Ref ID: 29223]

BWXT Y-12, 2000, *Recycled Uranium Mass Balance Project Y-12 National Security Complex Site Report*, Y/LB-16,036, Rev. 1, Y-12 National Security Complex, Oak Ridge, Tennessee, December. [SRDB Ref ID: 16500]

Callihan, D., and J. T. Thomas, 1959, “Accidental Radiation Excursion at the Oak Ridge Y-12 Plant—I. Description and Physics of the Accident,” *Health Physics*, volume 1, number 4, pp. 363–372. [SRDB Ref ID: 8606]

Chew, M. L., 2007, personal communication with G. D. Kerr, Kerr Consulting, Knoxville, Tennessee, April 10. [SRDB Ref ID: 31372]

Coleman, R. L., C. G. Hudson, and P. A. Plato, 1983, “Depth-Dose Curves for ^{90}Sr and Natural and Depleted Uranium in Mylar,” *Health Physics*, volume 44, number 4, pp. 395–402. [SRDB Ref ID: 12288]

DOE (U.S. Department of Energy), 2004, *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities*, DOE-STD-1136-2004, Washington, D.C., December. [SRDB Ref ID: 18881]

Dudney, R. A., 1956, “Photographic Dosimetry,” in *Radiation Dosimetry, 2nd Edition*, G. J. Hine and G. L. Brownnell, editors, Academic Press, New York, New York, Volume II, pp. 299-355.

Eckerman, K. F., 2003, *ICRP38 Computer Program (Ver. 1.0)*, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Eckerman, K. F., R. J. Westfall, J. C. Ryman, and M. Cristy, 1994, “Availability of Nuclear Decay Data in Electronic Form, Including Beta Spectra Not Previously Published,” *Health Physics*, volume 67, number 4, pp. 338-345.

Ehrlich, M., 1962, *The Use of Film Badges for Personnel Monitoring*, Safety Series No. 8, International Atomic Energy Agency, Vienna, Austria.

Elandt-Johnson, R. C., and N. L. Johnson, 1980, *Survival Models and Data Analysis*, John Wiley & Sons, New York, New York.

Emlet, L. B., 1952, “Contamination Control: Appendix A – Health Physics Aspects,” letter to R. C. Armstrong (U.S. Atomic Energy Commission, Oak Ridge Operations), Union Carbide Nuclear Corporation, Oak Ridge, Tennessee, July 21. [SRDB Ref ID: 20122]

Emlet, L. B., 1956, “Radiation Protection at UCNC Production Facilities,” letter to S. R. Sharpie (U.S. Atomic Energy Commission), Union Carbide Nuclear Company, Oak Ridge, Tennessee, August 29. [SRDB Ref ID: 23616]

Frome, E. L., and J. P. Watkins, 2004, *Statistical Analysis of Data with Non-detectable Values*, ORNL/TM-2004/146, UT Battelle, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August. [SRDB Ref ID: 24176]

Handloser, J. S., 1959, *Health Physics Instrumentation*, Pergamon Press, Oxford, England.

Henderson, 1991, *Evaluation of Radiation Exposure in Metal Preparation Depleted Uranium Process Areas*, Y/DQ--5/R1, Martin Marietta Energy Systems, Y-12 Plant, Oak Ridge, Tennessee, May. [SRDB Ref ID: 8538]

Howell, R. L., and Z. Batte, 1982, *Thermoluminescent Dosimetry for Union Carbide Corporation Nuclear Division Personnel*, Y/DK-291, Union Carbide Corporation, Oak Ridge, Tennessee, April 15. [SRDB Ref ID: 8603]

Hurst, G. S., R. H. Ritchie, and L. C. Emerson, 1959, “Accidental Radiation Excursion at the Oak Ridge Y-12 Plant—III. Determination of Radiation Doses,” *Health Physics*, volume 2, pp. 121–133. [SRDB Ref ID: 10132]

IAEA (International Atomic Energy Agency), 1974, *Evaluation of Radiation Emergencies and Accidents: Selected Criteria and Data*, Technical Reports Series No. 152, Vienna, Austria, March 29.

ICRP (International Commission on Radiological Protection), 1977, *Recommendations of the International Commission on Radiological Protection*, Publication 26, Pergamon Press, Oxford, England.

ICRP (International Commission on Radiological Protection), 2002, *Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values*, Publication 89, Pergamon Press, Oxford, England.

ICRU (International Commission on Radiation Units and Measurements), 1997, *Dosimetry of External Beta Rays for Radiation Protection*, Report 56, Bethesda, Maryland.

Johnson, N. L, S. Kotz, and N. Balakrishnan, 1995, *Continuous Univariate Distributions, Second Edition*, J. Wiley and Sons, New York, New York.

Jones, D. A., 1971, *Evaluation of Personal Monitoring Films for Y-12 Security Meter Badge*, Y-DD-85, Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 8530]

Kang, J., and F. N. von Hippel, 2001, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel," *Science & Global Security*, volume 9, number 1, pp. 1–32. [SRDB Ref ID: 21218]

Larson, C. E., 1949, "Finger Film Pad," letter to H. Blatz (U.S. Atomic Energy Commission), Carbide and Carbon Chemicals Corporation, Y-12 Plant, Oak Ridge, Tennessee, December 16. [SRDB Ref ID: 4298]

Lejeune, M., and G. D. Faulkenberry, 1982, "A Simple Predictive Density Function," *Journal of the American Statistical Association*, volume 77, number 379, pp. 654–657.

McLendon, J. D., 1958, "Change in Y-12 Film Badge Program," memorandum to E. W. Bailey et al., Union Carbide Nuclear Company, Oak Ridge, Tennessee, March 31. [SRDB Ref ID: 20093]

McLendon, J. D., 1960, "Personnel Radiation Exposure Data," memorandum to G. W. Flack, Union Carbide Nuclear Company, Y-12 Plant, Oak Ridge, Tennessee, August 25. [SRDB Ref ID: 3694]

McLendon, J. D., 1962, "Supplementary Film Badge Program," memorandum to L. E. Burkart, Union Carbide Nuclear Company, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 19800]

McLendon, J. D., 1963, *Y-12 Radiation Safety Manual*, Y-KB-29, Union Carbide Corporation, Oak Ridge, Tennessee, October 31. [SRDB Ref ID: 8541]

McLendon, J. D., R. G. Affel, A. G. Bailey, K. A. Davis, and E. D. Gupton, 1980, *External Radiation Monitoring of Union Carbide Nuclear Division Personnel*, Y/DD-268, Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee, March 23. [SRDB Ref ID: 8589]

McRee, P. C., C. M. West, and J. D. McLendon, editors, 1965, *Y-12 Radiation Safety Manual*, Y-1401–Revised, Union Carbide Corporation, Nuclear Division, Oak Ridge, Tennessee, May 11. [SRDB Ref ID: 8536]

Morgan, K. Z., 1961, "Dosimetry Requirements for Protection from Ionizing Radiation," *Selected Topics in Radiation Dosimetry, Proceedings of the Symposium on Selected Topics in Radiation Dosimetry, Sponsored by and Held in Vienna 7-11 June 1960*, International Atomic Energy Agency, Vienna, Austria, pp. 3–23. [SRDB Ref ID: 8345]

Murray, R., 1948a, *Health Physics Progress Report, January 1 - 31, 1948*, Y-120, Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee, February 16. [SRDB Ref ID: 8602, p. 476]

Murray, R., 1948b, *Health Physics Progress Report, February 1 - 29, 1948*, Y-134, Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee, March 17. [SRDB Ref ID: 8602, p. 469]

NAS (National Academy of Sciences), 2005, *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, National Academy Press, Washington, D.C.

NBS (National Bureau of Standards), 1954, *Permissible Dose from External Sources of Ionizing Radiation, Recommendations of the National Committee on Radiation Protection*, Handbook 59, U.S. Department of Commerce, Washington, D.C., September 24. [SRDB Ref ID: 11111, p. 16]

ORAUT (Oak Ridge Associated Universities Team), 2004a, *Technical Information Bulletin: Individual Dose Adjustment Procedure for Y-12 Dose Reconstruction*, ORAUT-OTIB-0013, Rev. 00, Oak Ridge, Tennessee, September 9.

ORAUT (Oak Ridge Associated Universities Team), 2004b, *Accounting for Incomplete Personal Monitoring Data on Penetrating Gamma-Ray Doses to Workers in Radiation Areas at the Oak Ridge Y-12 Plant Prior to 1961*, ORAUT-PROC-0042, Rev. 00, Oak Ridge, Tennessee, September 9.

ORAUT (Oak Ridge Associated Universities Team), 2005a, *Historical Evaluation of the Film Badge* Dosimetry Program *at the Y-12 Facility in Oak Ridge, TN, Part 1 – Gamma Radiation,* ORAUT-RPRT-0032, Rev. 00, Oak Ridge, Tennessee, April 13.

ORAUT (Oak Ridge Associated Universities Team), 2005b, *Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Facility in Oak Ridge, Tennessee: Part 2 – Neutron Radiation*, ORAUT-RPRT-0033, Rev. 00, Oak Ridge, Tennessee, April 13.

ORAUT (Oak Ridge Associated Universities Team), 2005c, *Interpretation of Dosimetry Data for Assignment of Shallow Dose*, ORAUT-OTIB-0017, Rev. 01, Oak Ridge, Tennessee, October 11.

ORAUT (Oak Ridge Associated Universities Team), 2005d, *External Radiation Monitoring at the Y-12 Facility During the 1948-1949 Period*, ORAUT-OTIB-0047, Rev. 00, Oak Ridge, Tennessee, September 20.

ORAUT (Oak Ridge Associated Universities Team), 2005e, *Technical Basis Document for the Y-12 National Security Complex – Site Description*, ORAUT-TKBS-0014-2, Rev. 01 PC-2, Oak Ridge, Tennessee, October 11.

ORAUT (Oak Ridge Associated Universities Team), 2006a, *A Standard Complex-Wide Methodology for Overestimating External Doses Measured with Film Badge Dosimeters*, ORAUT-OTIB-0010, Rev. 01, Oak Ridge, Tennessee, May 5.

ORAUT (Oak Ridge Associated Universities Team), 2006b, *Technical Basis Document for the Y-12 National Security Complex - Occupational External Dosimetry*, ORAUT-TKBS-0014-6, Rev. 00 PC-3, Oak Ridge, Tennessee, May 11.

ORAUT (Oak Ridge Associated Universities Team), 2006c, *External Radiation Dose Estimates for Individuals Near the 1958 Criticality Accident at the Oak Ridge Y-12 Plant*, ORAUT-OTIB-0057, Rev. 00, Oak Ridge, Tennessee, May 15.

Oxley, L. S., 2001, *Technical Basis for the External Dosimetry Program at the Y-12 National Security Complex*, RCO/TBD-007, Revision 3, BWXT Y-12, Y-12 National Security Complex, Oak Ridge, Tennessee, August 2. [SRDB Ref ID: 8467]

Patterson, G. R. Jr., 1958, “Film Badge Exchange,” memorandum to J. C. Hart, Union Carbide Nuclear Company, Oak Ridge, Tennessee, April 11. [SRDB Ref ID: 28128]

Patterson, G. R., Jr., C. M. West, and J. D. McLendon, 1957, *The Y-12 Health Physics Program*, Y-1186 Deleted Revision, Union Carbide Nuclear Company, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 14022]

RDCT (R Development Core Team), 2004, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, ISBN-3-900051-00-3, Vienna, Austria.

Reavis, J. P., 1958, “Frequency of Film Badge Analysis,” memorandum to C. M. West, Union Carbide Nuclear Company, Y-12 Plant, Oak Ridge, Tennessee, October 8. [SRDB Ref ID: 20094]

Rutherford, B. F., 2005, personnel communication with G. D. Kerr, Kerr Consulting, Knoxville, Tennessee, July 26. [SRDB Ref. ID: 31372]

Schneider, S., D. C. Kocher, G. D. Kerr, P. A. Scofield, F. R. O’Donnell, C. R. Mattsen, S. J. Cotter, J. S. Bogard, J. S. Bland, and C. Wiblin, 1999, *Systematic Radiological Assessment of Exemptions for Source and Byproduct Materials*, NUREG-1717, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C., June.

Sherrill, M. W., and W. O. Tucker, 1973, *Evaluation of New Film Badge Reader and Revised Exposure Computations*, Y-DK-111, Union Carbide Corporation, Nuclear Division, Oak Ridge, Tennessee, October 12. [SRDB Ref ID: 8590]

Shleien, B., L. A. Slaback, Jr., and B. K. Birky, editors, 1998, *Handbook of Health Physics and Radiological Health, Third Edition*, Williams & Wilkins, Baltimore, Maryland, January.

Souleyrette, M. L., 2003, *Y-12 National Security Complex, Summary of Historical Monitoring Techniques Provided to NIOSH for EEOICPA Data Requests*, Revision 0, BWXT Y-12, Y-12 National Security Complex, Oak Ridge, Tennessee, February 18. [SRDB Ref ID: 8586]

Struxness, E. G., 1948a, *Health Physics - Industrial Hygiene Progress Report, May 1 - 31, 1948*, Y-181/1R, Y-12 Plant, Oak Ridge, Tennessee, June 16. [SRDB Ref ID: 8602, p. 457]

Struxness, E. G., 1948b, *Health Physics – Industrial Hygiene Progress Report, August 1 - 31 1948*, Y-237/1R, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, September 9. [SRDB Ref ID: 6844]

Struxness, E. G., 1949a, *Health Physics - Hygiene Progress Report, May 1 - 31, 1949*, Y-429/1R, Y-12 Plant, Oak Ridge, Tennessee, July 11. [SRDB Ref ID: 8602, p. 296]

Struxness, E. G., 1949b, *Health Physics-Industrial Hygiene Progress Report, December 1-31, 1948*, Y-318/1R, Y-12 Plant, Oak Ridge, Tennessee, January 19. [SRDB Ref ID: 8602, p. 364]

Struxness, E. G., 1951a, *Health Physics Progress Report, November 1, 1950 - December 31, 1950*, Y-780, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, June 14. [SRDB Ref ID: 8602, p. 215]

Struxness, E. G., 1951b, *Health Physics Progress Report, January 1, 1951 – June 30, 1951*, Y-836, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, December 15. [SRDB Ref ID: 8602, p. 257]

Struxness, E. G., 1952, *Health Physics Progress Report, July 1, 1951 - December 31, 1951*, Y-858, H. F. Ballenger, editor, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, March 15. [SRDB Ref ID: 13055]

Struxness, E. G., 1954a, *Health Physics Progress Report, July 1, 1952 through December 31, 1952*, Y-1066, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, April 30. [SRDB Ref ID: 8602, p. 85]

Struxness, E. G., 1954b, *Health Physics Progress Report – January 1, 1953 through June 30, 1953*, Y-1070, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, June. [SRDB Ref ID: 8602, p. 53]

Thornton, W. T., D. M. Davis, and E. D. Gupton, 1961, *The ORNL Badge Dosimeter and Its Personnel Monitoring Applications*, ORNL-3126, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [SRDB Ref ID: 8573]

UCNC (Union Carbide Nuclear Company), 1958, *Accidental Radiation Excursion at the Y-12 Plant, June 16, 1958, Final Report*, Y-1234, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 4439]

UCNC (Union Carbide Nuclear Company), 1963a, *Y-12 Plant Quarterly Health Physics Report – Fourth Quarter CY 1962*, Y-KB-26, Oak Ridge, Tennessee, March 5, 1963. [SRDB Ref ID: 23618]

UCNC (Union Carbide Nuclear Company), 1963b, *Y-12 Plant Quarterly Health Physics Report – Third Quarter CY 1962*, Y-KB-24, Y-12 Plant, Oak Ridge, Tennessee, February 7. [SRDB Ref ID: 23617]

Watkins, J. P., J. L. Reagan, D. L. Cragle, E. L. Frome, C. M. West, D .J. Crawford-Brown, and W. G. Tankersley, 1993, *Data Collection, Validation, and Description for the Oak Ridge Nuclear Facilities Mortality Study,* ORISE 93/J-42, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, October. [SRDB Ref ID: 10133]

West, C. M., 1955, “Tabulation of Direct Radiation Findings,” internal correspondence to F. Baker, Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee, June 27. [SRDB Ref ID: 19808]

West, C. M., 1956, “Listings of External Exposure Records on IBM Sheets,” memorandum to P. Johnson, Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee, March 5. [SRDB Ref ID: 19803]

West, C. M., and E. Roberts, Jr., 1962, *Health Physics Experience During Processing of U-233 in Y-12 Plant*, Y-KB-19, Union Carbide Nuclear Company, Y-12 Plant, Oak Ridge, Tennessee, September 12. [SRDB Ref ID: 11598]

West, C. M., 1965, *Health Physics Considerations Associated with Thorium Processing*, Y-KB-53, Y-12 Plant, Oak Ridge, Tennessee, March 10. [SRDB Ref ID: 11596]

West, C. M., 1974, “Health Physics Considerations Associated with Processing of ^{233}U,” internal correspondence to R. B. Burditt, Union Carbide Nuclear Division, Y-12 Plant, Oak Ridge, Tennessee, May 10. [SRBD Ref ID: 28129]

West, C. M., 1981, “Discrepancy in 1954 Y-12 Film Badge Results,” letter to H. L. Fore (Oak Ridge Gaseous Diffusion Plant), Union Carbide Corporation, Oak Ridge, Tennessee, August 18. [SRDB Ref ID: 28125]

West, H. [C. M.], 1993a, “Brief History of the Y-12 External Monitoring Program,” internal memorandum to D. Cragle, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, June 7. [SRDB Ref ID: 8532]

West, H. [C. M.], 1993b, “Addendum to 'Brief History of the Y-12 External Monitoring Program',” memorandum to D. L. Cragle, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, June 15. [SRDB Ref ID: 13296]

Wilcox, W. J., Jr., 2001, *An Overview of the History of Y-12, 1942 - 1992, A Chronology of Some Noteworthy Events and Memoirs*, American Museum of Science and Energy, Oak Ridge, Tennessee, August. [SRDB Ref ID: 9609]

Wiley, S. W., 2004, “Y-12 Historical Radiation Standards,” letter to G. D. Kerr, BWXT Y-12, Knoxville, Tennessee, June 3. [SRDB Ref ID: 28131]

Wollan, R. O., 1954, “Health Physics Records,” letter to O. S. Hiestand, Jr. (U.S. Atomic Energy Commission, Office of Assistant Counsel General), Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee, May 24. [SRDB Ref ID: 19810]

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES
Page 1 of 14

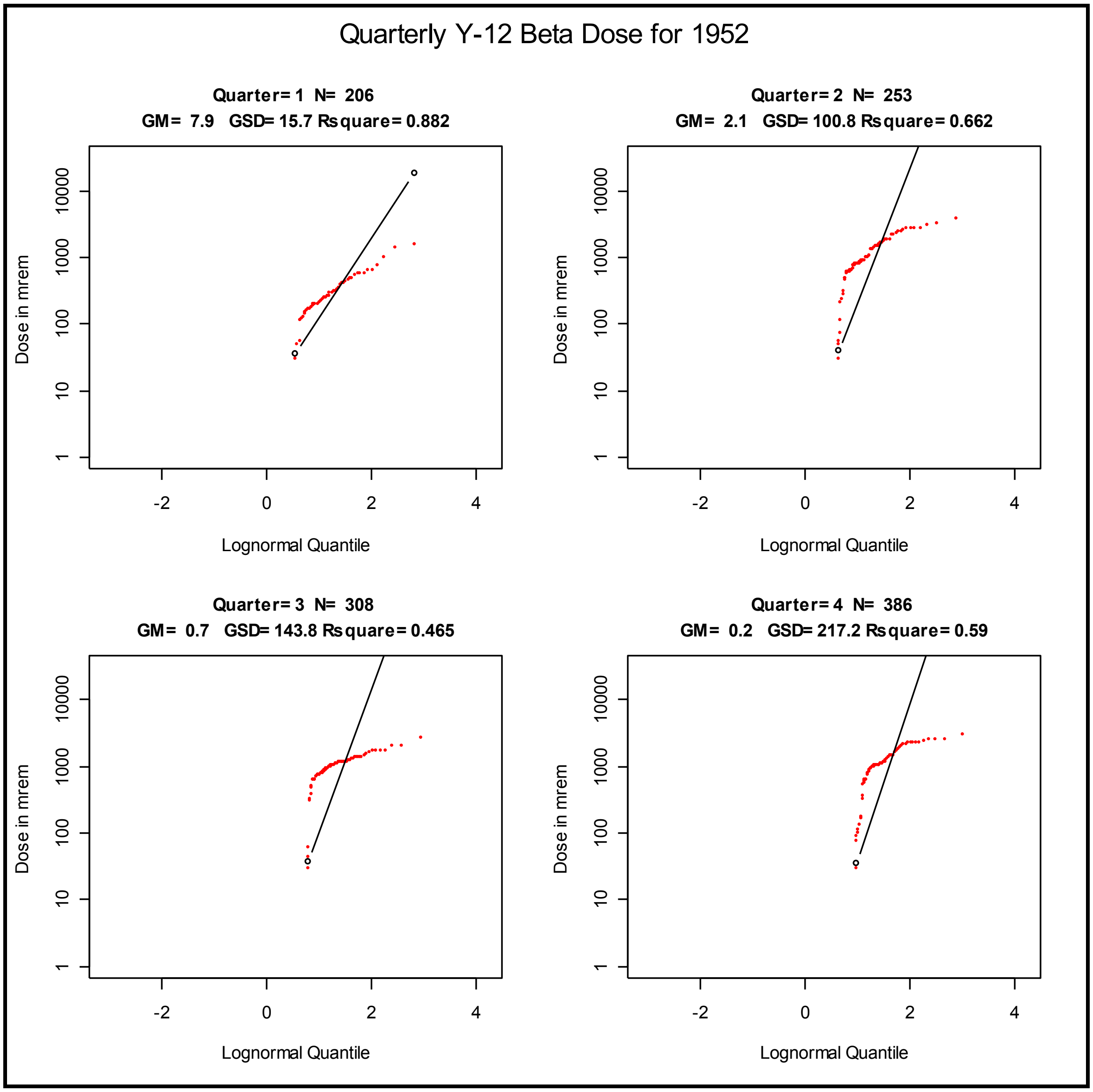

Figure A-1. Q-Q plots for 1952.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

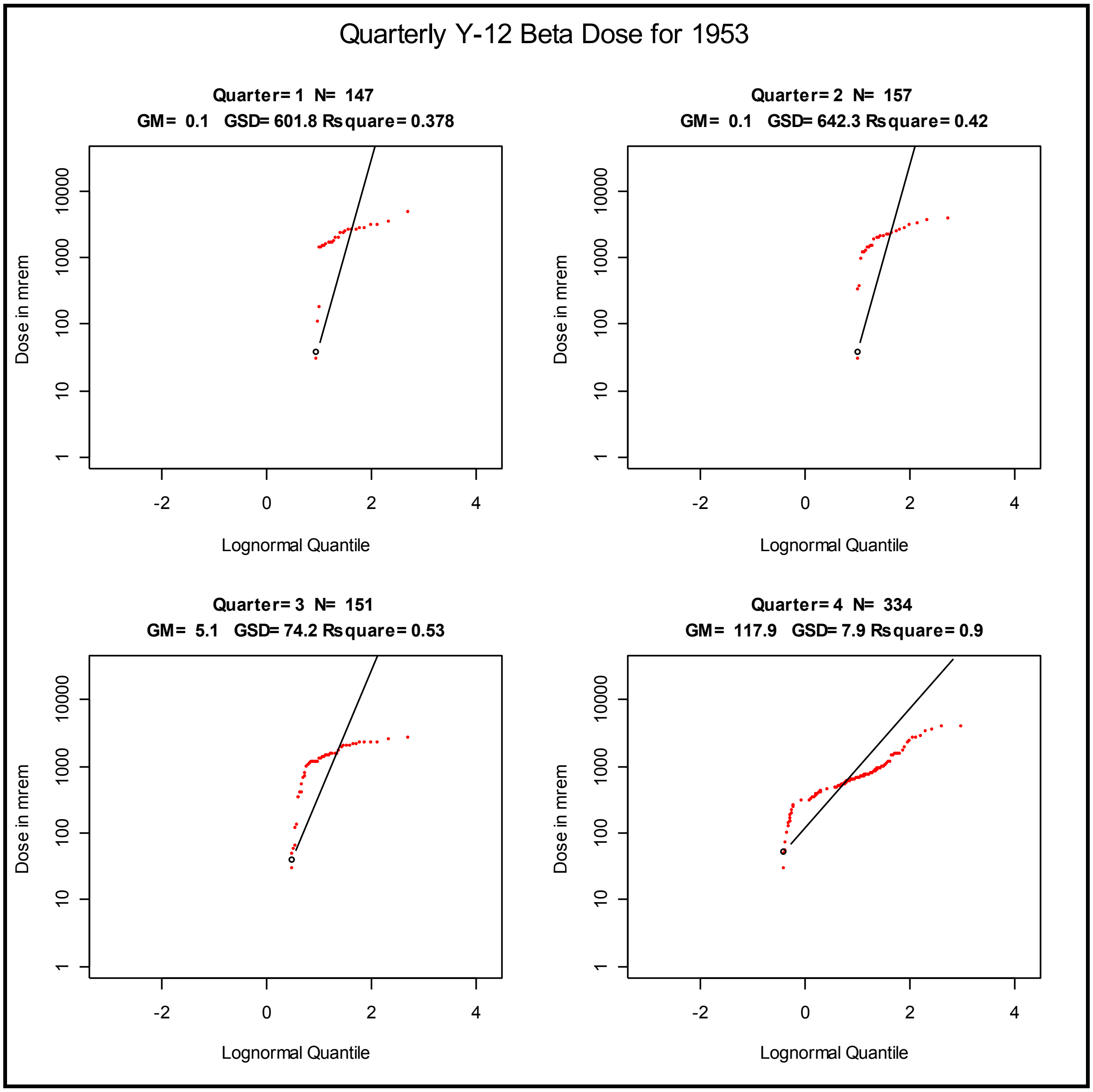

Figure A-2. Q-Q plots for 1953.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

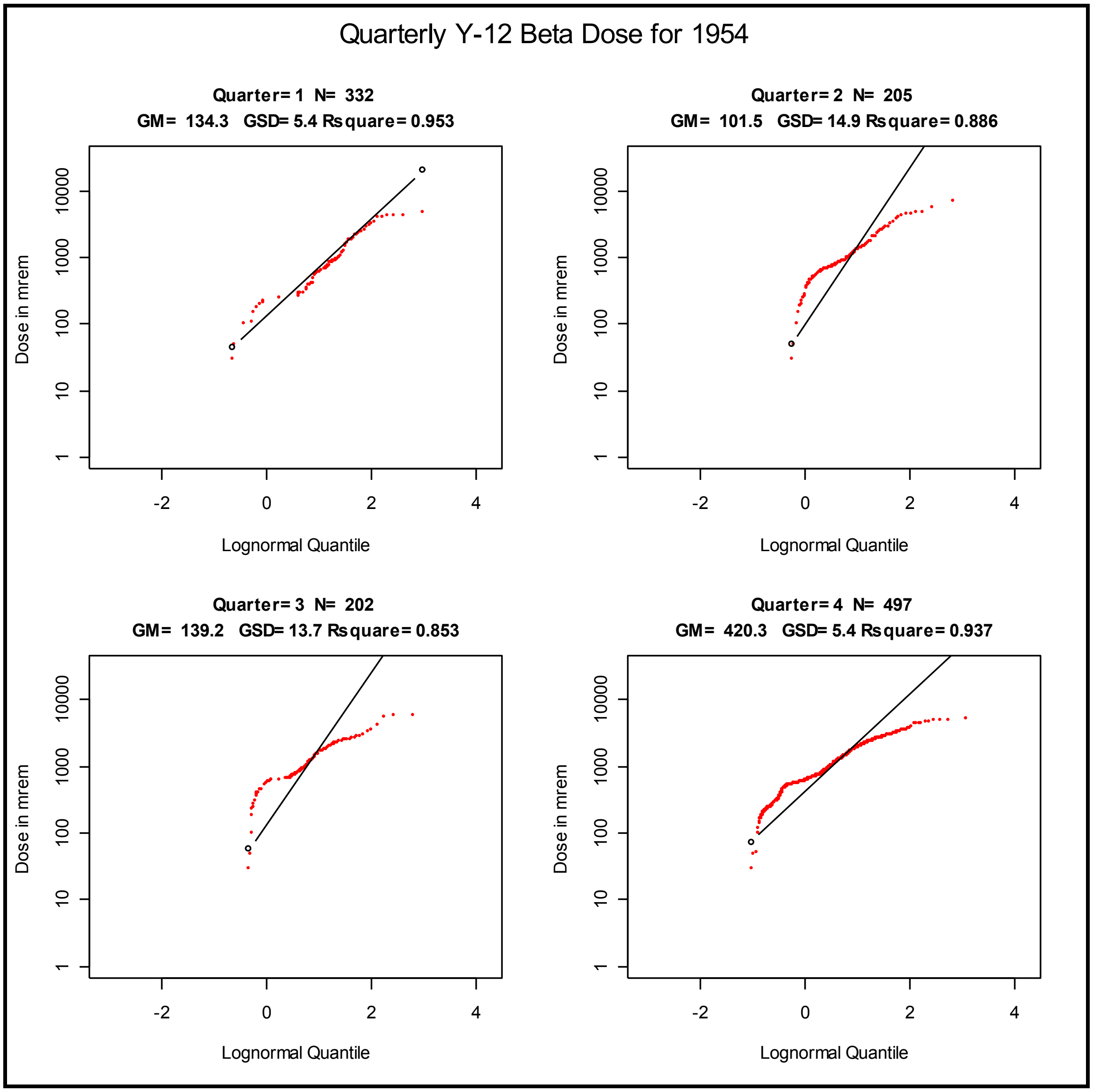

Figure A-3. Q-Q plots for 1954.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES
Page 4 of 14

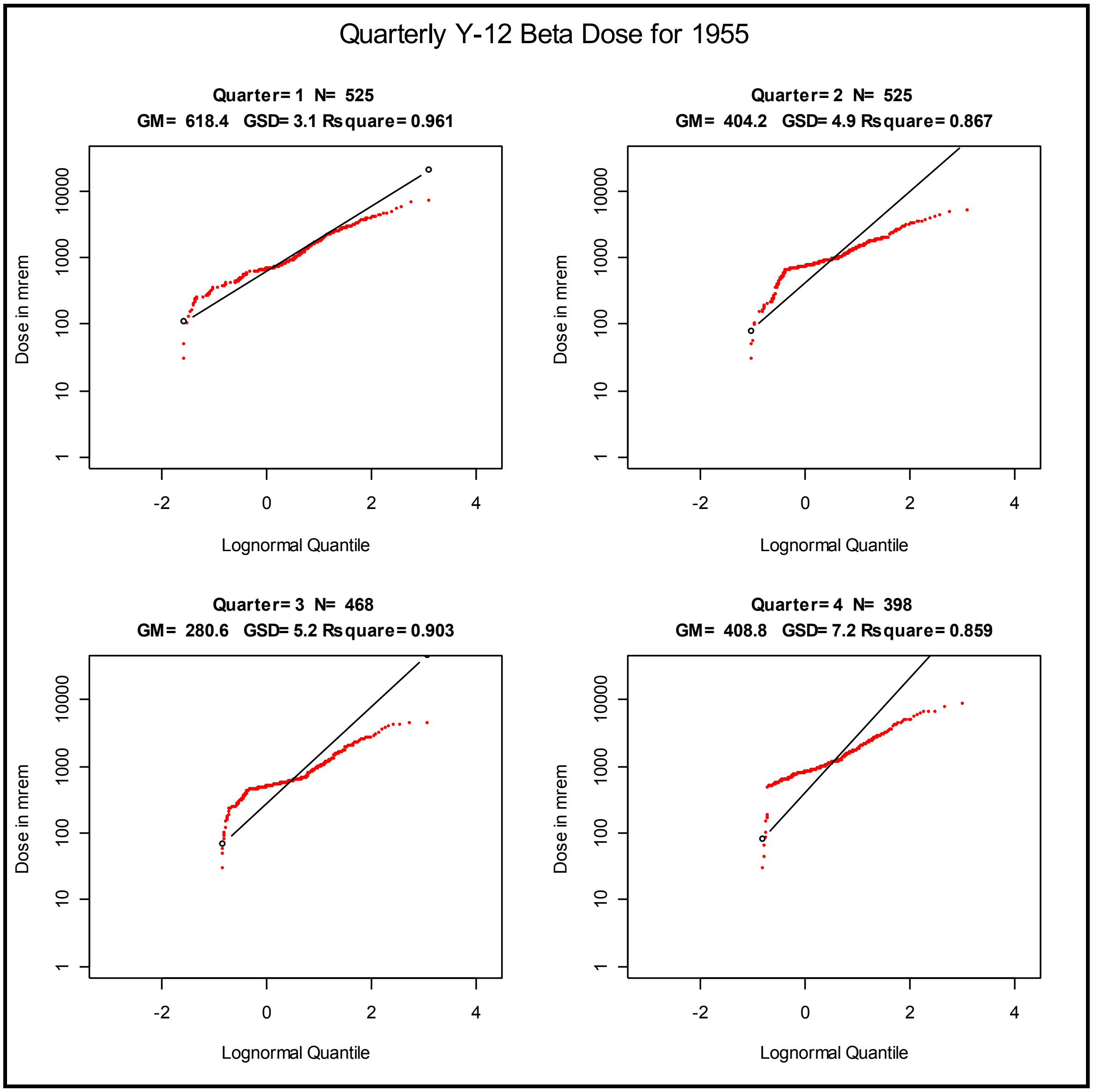

Figure A-4. Q-Q plots for 1955.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

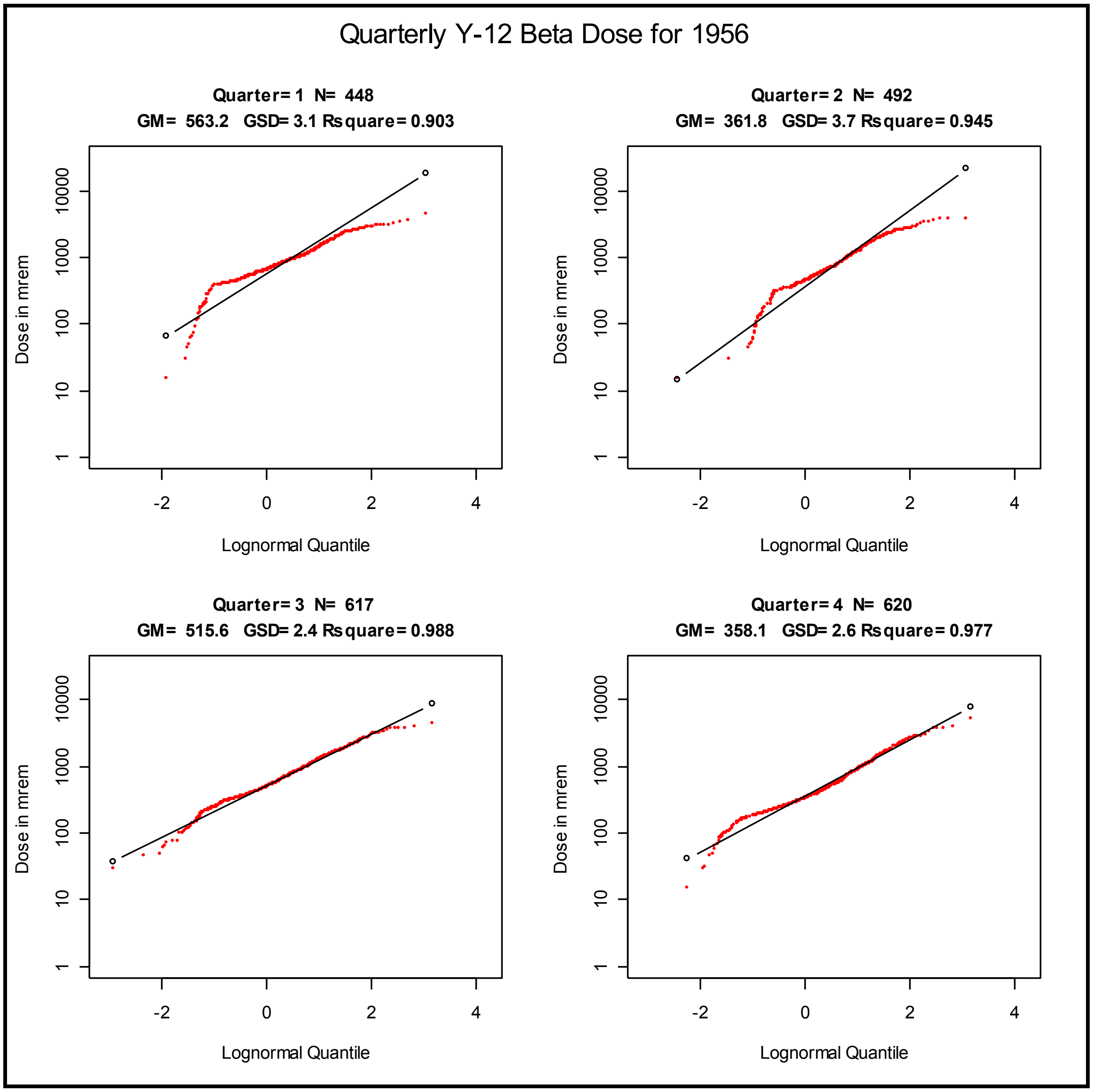

Figure A-5. Q-Q plots for 1956.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

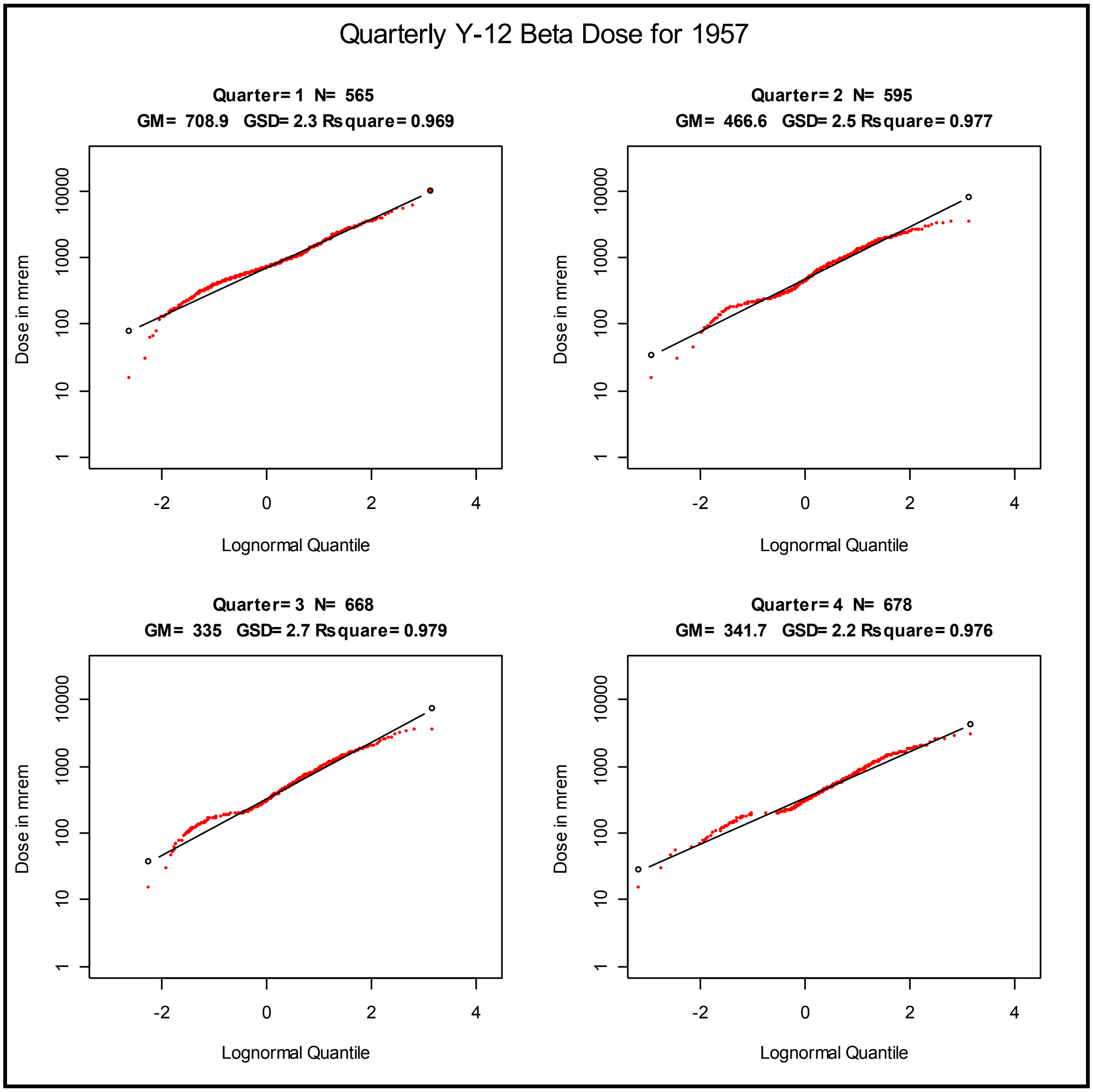

Figure A-6. Q-Q plots for 1957.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

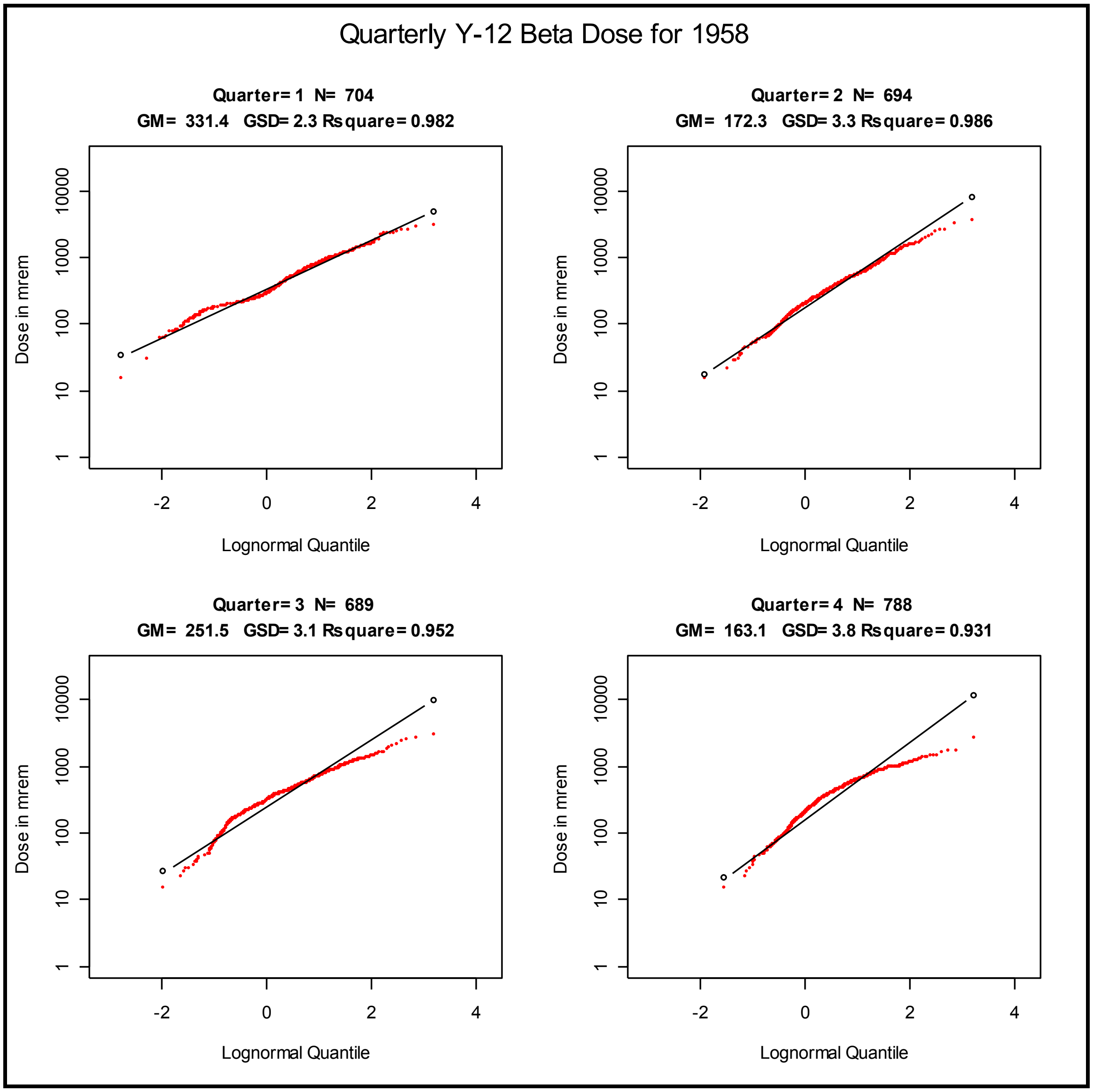

Figure A-7. Q-Q plots for 1958.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES
Page 8 of 14

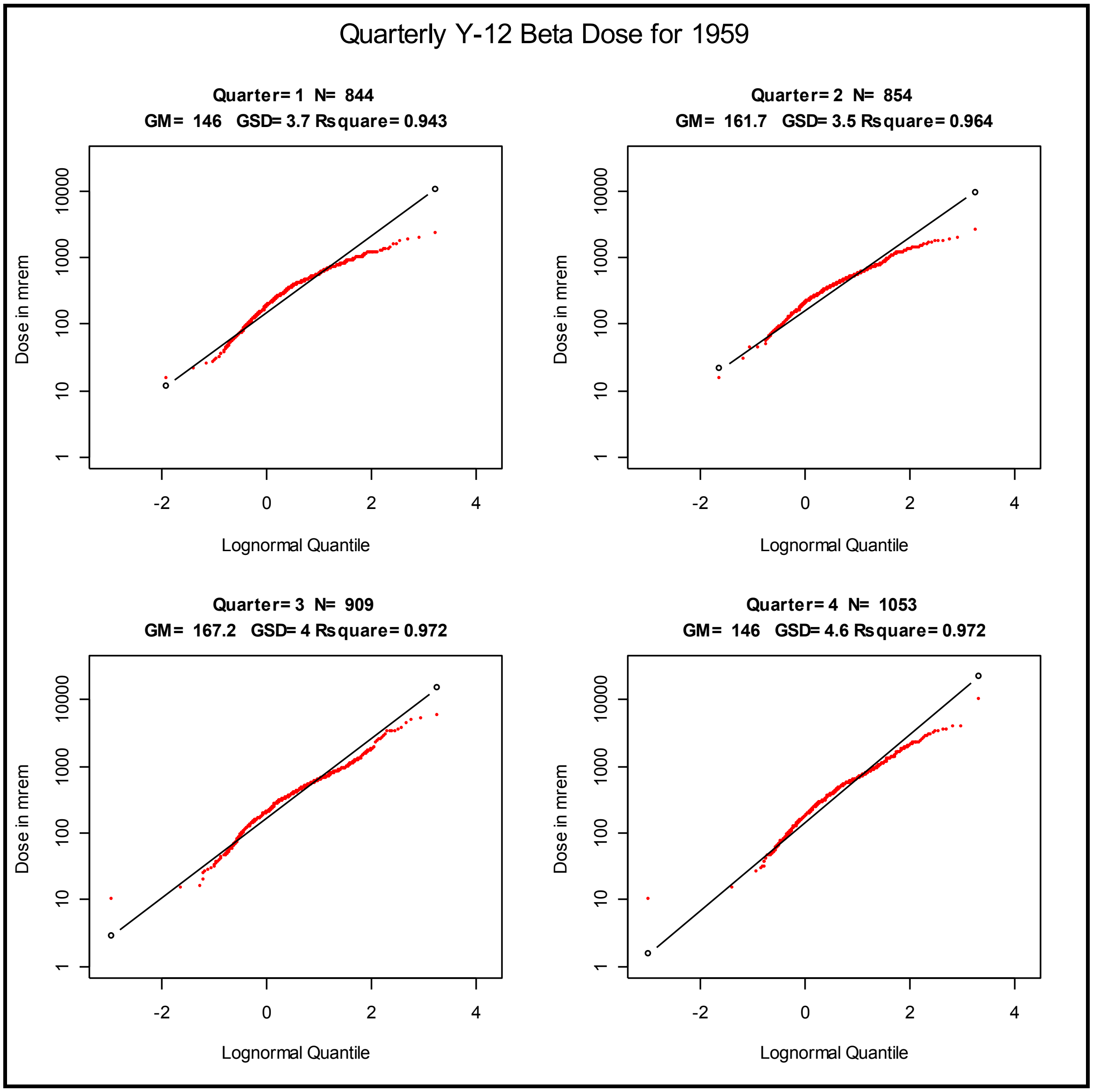

Figure A-8. Q-Q plots for 1959.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

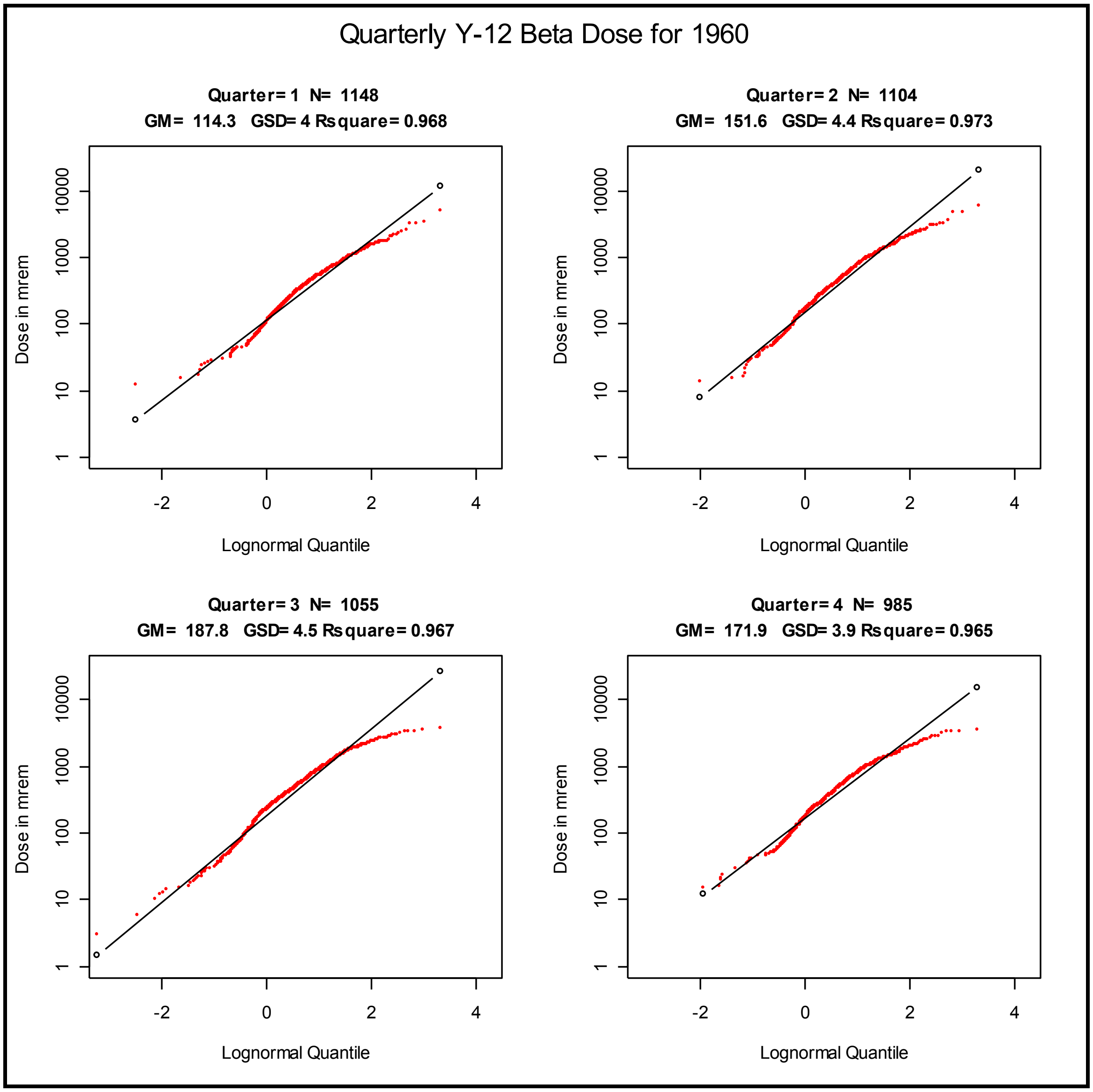

Figure A-9. Q-Q plots for 1960.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

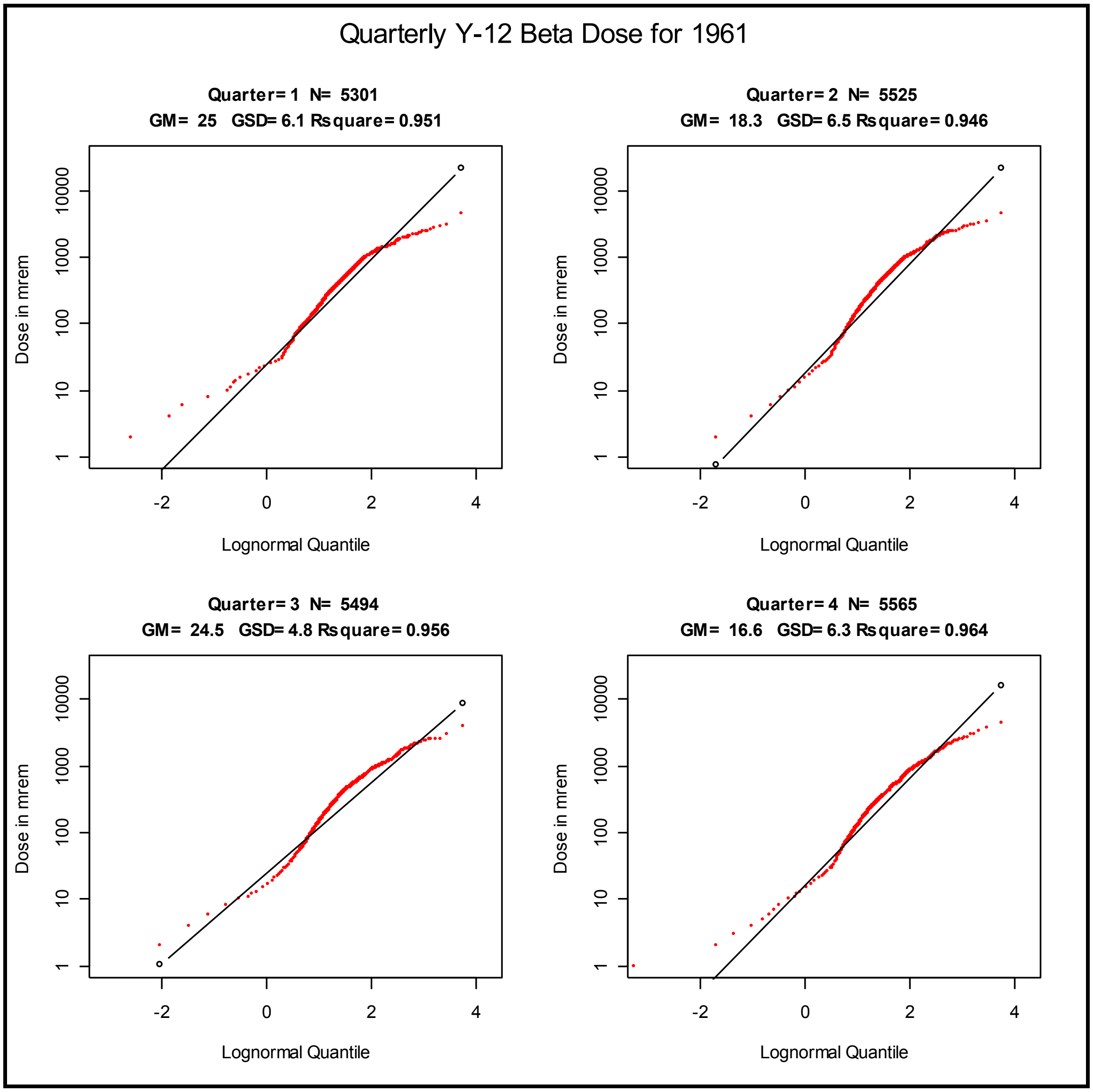

Figure A-10. Q-Q plots for 1961.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES
Page 11 of 14

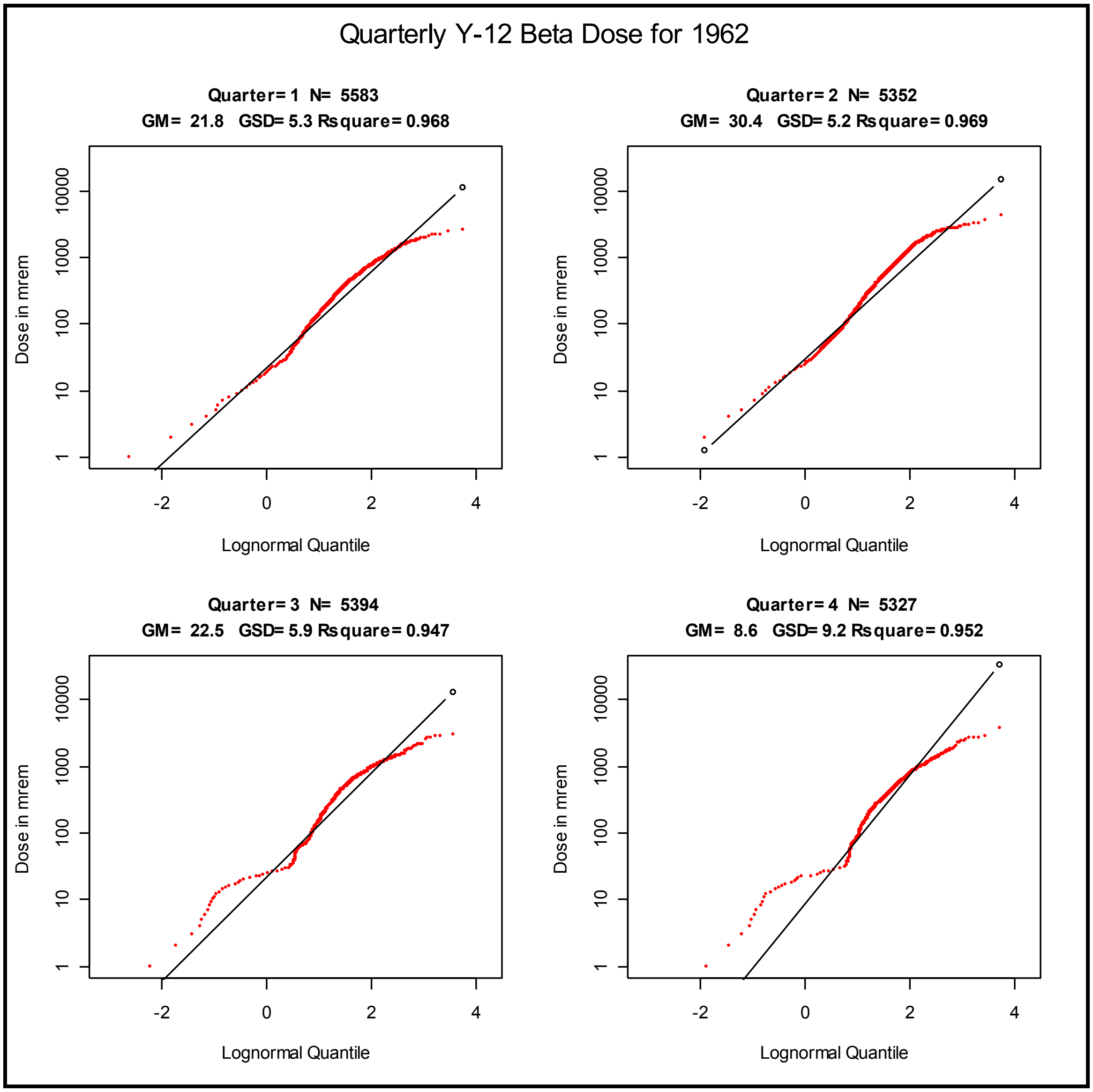

Figure A-11. Q-Q plots for 1962.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

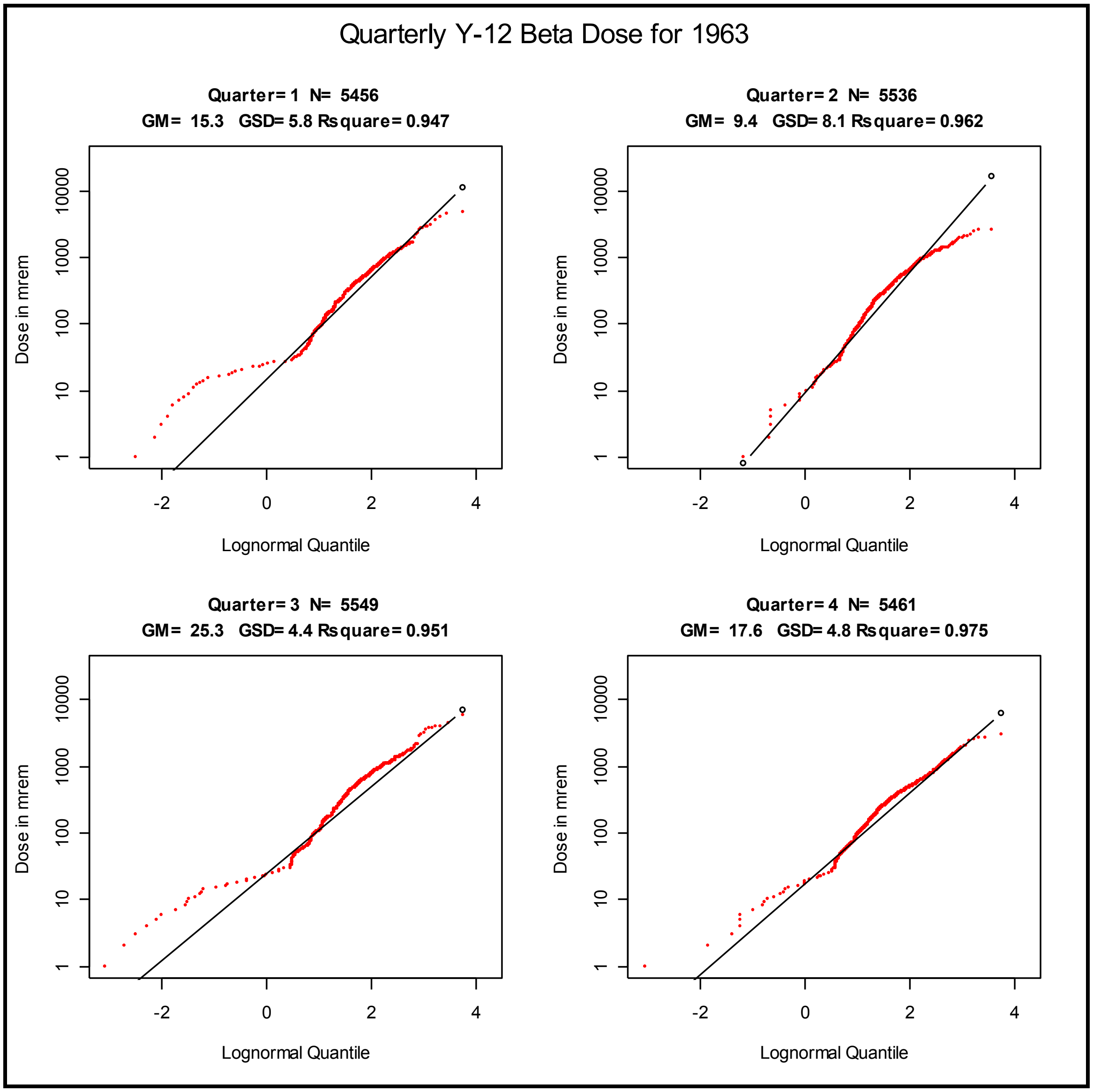

Figure A-12. Q-Q plots for 1963.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES
Page 13 of 14

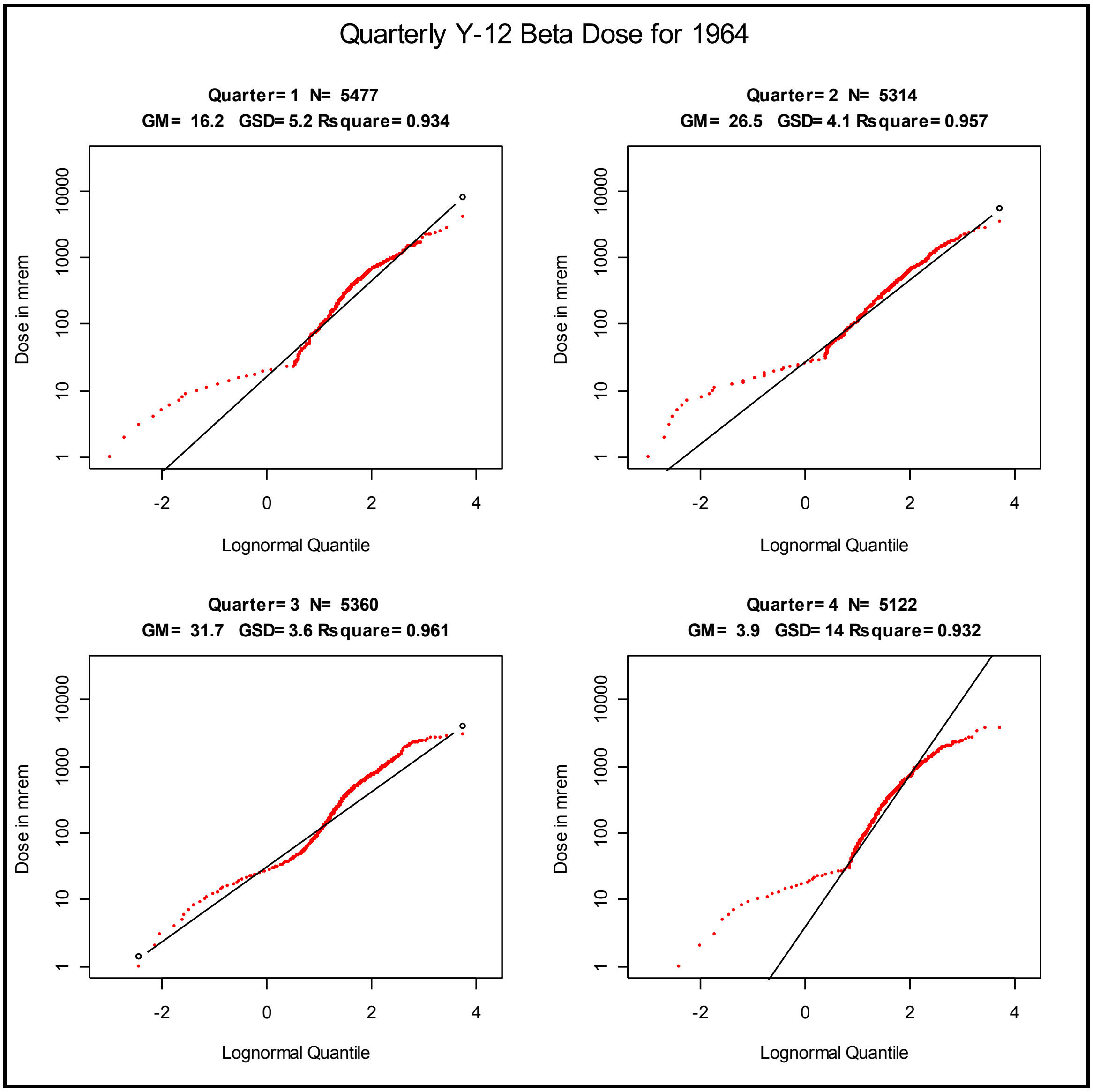

Figure A-13. Q-Q plots for 1964.

ATTACHMENT A
LOGNORMAL QUANTILE-QUANTILE PLOTS FOR QUARTERLY BETA DOSES

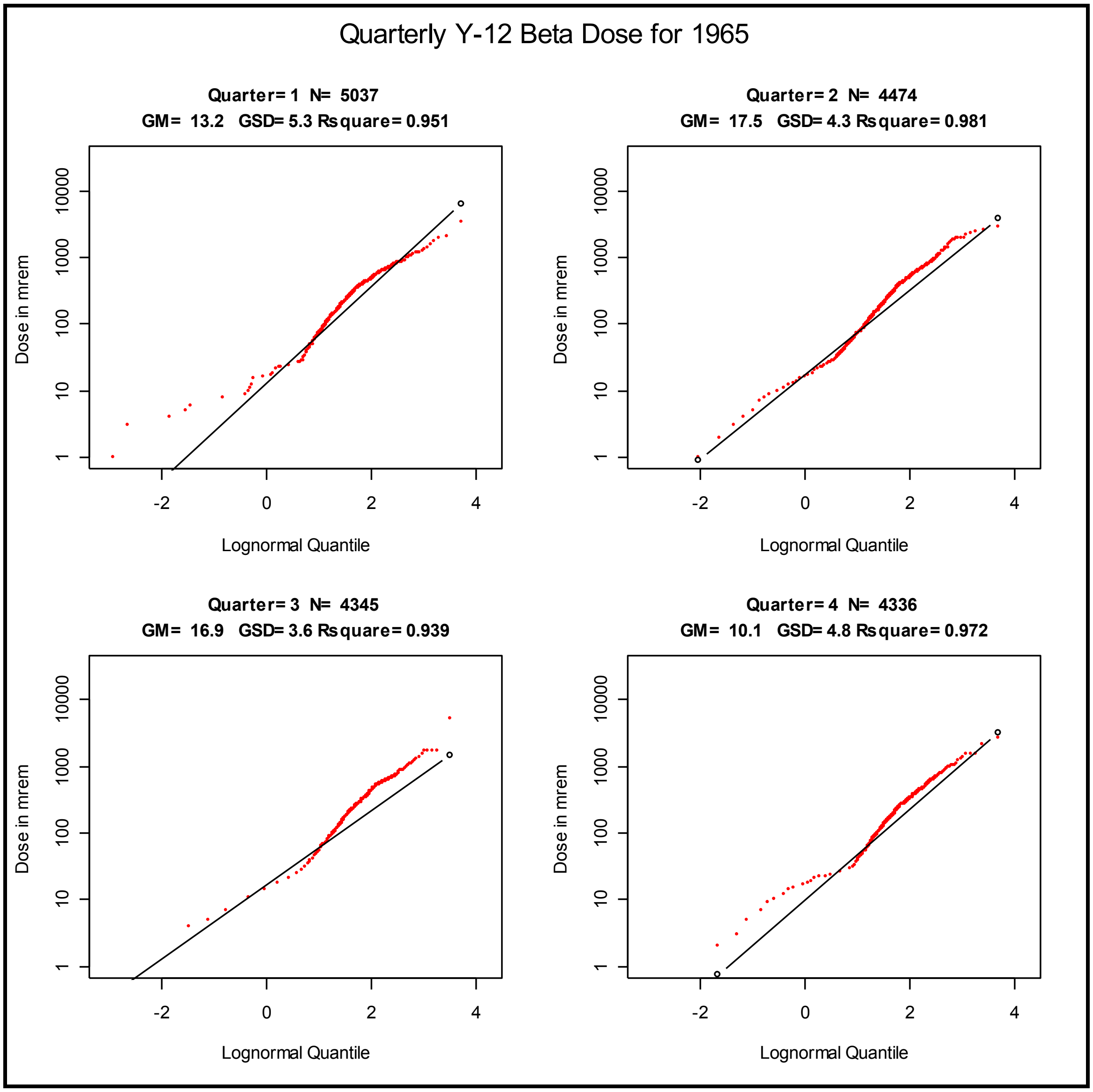

Figure A-14. Q-Q plots for 1965.